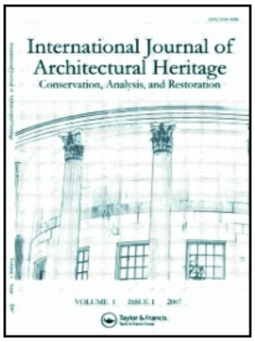

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The Influence of Pathological Situations on Churches' Functionality: An Approach Based on Historical Records

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ABSTRACT
This study identifies the main anomalies that may occur in historical buildings, analyzing their related causes, and estimating the influence of pathological situations on the buildings' functionality. This information is essential to support qualified, conscientious, and sustainable rehabilitation interventions on sets of heritage buildings with homogeneous constructive characteristics. A fuzzy expert system was used to estimate the serviceability of buildings, performed based on historical records, over a long period of time, evaluating the influence of the pathological situations to establish the rehabilitation actions. The methodology includes 17 variables, (vulnerabilities and external risks damages), which determine a functionality index of the constructions analyzed. The application of historical data allows knowing the past behavior and performance of the buildings. These data can provide useful information for the definition of preventive maintenance plans, considering financial, social, and environmental requirements and their more frequent anomalies. A total of 390 records in a sample of 20 parish churches located in southwestern Spain were gathered. This study discussed the effects of the most common anomalies observed in these buildings, concluding that controlling moisture and timber-related anomalies is crucial to ensure the building's serviceability over time.

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anomalies; built heritage; diagnosis; pathology; serviceability

1. Introduction

Currently, it has been estimated that 50% of all buildings' refurbishments in European cities are related, in some way, with the preservation of the built heritage (European Commission 2000; Vicente et al. 2015). Evaluating the degradation condition of buildings over time, as well as predicting their future performance, is essential to establish the necessary repairs and rehabilitation actions. In this sense, the maintenance of architectural heritage buildings requires methods, strategies and efficient plans (Vicente, Ferreira, and da Silva 2015).

The knowledge on past renewal and renovation processes on buildings, including the identification of the deterioration processes, main anomalies and probable causes that lead to the intervention, should be the basis of the definition of maintenance plans and strategies. As mentioned by Talon et al. (2005), to improve the design and management of buildings, it is essential to know "how" and "when" the buildings will be degraded or will fail, which allows knowing "how", "when", and "which" component should be intervened.

Within this context, and considering the investment required for the maintenance and repair of the built heritage, it is essential to define, validate, and disseminate tools that may be useful to planning an appropriate maintenance strategy for architectural heritage (Neto and de Brito 2012). Therefore, this study intends to present an innovative contribution in the analysis of historical data of built heritage, evaluating the influence of pathological situations on the functionality of the buildings' over time. Consequently, this study correlates the physical condition of the buildings (through the identification of the anomalies observed and the buildings' physical degradation) with the functional obsolescence of the buildings (based on the definition of a numerical index, obtained through an expert survey). In this approach, 20 parish churches located in Seville were studied. The effects of different types of anomalies in some buildings are liable to considerably decrease their performance, compromising their ability to fulfil the functional requirements. Thus, this study identifies the most relevant anomalies to the loss of functional performance of the churches analyzed, as well as their relevance to establish repair and rehabilitation actions.

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2. Buildings' degradation

During their service life, buildings must comply with an assortment of demands that can be grouped as: functional; environmental; economic; legal; users' requirements; among others (Watt 2009). Inevitably, all buildings experience a deterioration process, starting from the instant they are built (Gaspar and de Brito 2005), which is not necessarily the result of design or execution defects. As a matter of fact, as mentioned by Rodrigues, Teixeira, and Cardoso (2011), the deterioration mechanisms are the consequence of the interaction of two independent variables: the building and the surrounding environment.

In this decay process, the building progressively tends to fail in fulfilling the users' needs and expectations, which unavoidably lead to the end of the buildings service life, which usually occurs due to their physical degradation or their functional obsolescence, or a combination of these two situations (Gaspar and de Brito 2005).

The evolution rate of anomalies in the earlier stage of the buildings' life cycle tends to apparently stabilize over time but accelerates again near the end of the service life (Silva, de Brito, and Gaspar 2016), due to the superimposition of more than one degradation mechanisms (Bordalo et al. 2011).

In the last decades, several studies have been put forward related with the inspection, diagnosis, and rehabilitation of the buildings' envelope (Gaião, de Brito, and Silvestre 2012; Neto and de Brito 2012; Silvestre and de Brito 2011; Garcez et al. 2012a,b). However, this type of research is not common in cultural heritage buildings, since some anomalies are usually seen as patina. Nevertheless, currently, the presence of anomalies such as cracking or moisture stains, are not easily acceptable, being considered as pathological situations, instead of age-value (Ferreira and Maximo 2013).

In reality, establishing a cause-effect relationship is a very complex task, given the variety of anomalies observed, which jeopardizes the determination and evaluation of the anomalies' causes based on their manifestations and consequences (Neto and de Brito 2012). In the built heritage, the most important causes of anomalies are related to the responses to physics and chemical actions, atmospherics agents and mechanical behavior of the material and components (Watt 2009).

2.1. Main built heritage anomalies

To standardize the reports and inspection files in a sample of heritage buildings, it is essential to create a classification system of the anomalies that could occur in these buildings. The systematization of the anomalies detected in heritage buildings is based on an extensive literature review, characterizing the main maintenance source elements influenced by these anomalies: E1—masonry (Athmani et al. 2015; Lordsleem 2016); E2—timber elements (Delgado, de Brito, and Silvestre 2013); E3—Roofs (Walter, de Brito, and Grandão Lopes 2005; Garcez et al. 2012a; b); E4—foundations (Poulos 2016; Carretero-Ayuso, Moreno-Cansado, and Cuerda-Correa 2015); and E5—mortars and claddings (Flores-Colen, de Brito, and de Freitas 2008; Neto and de Brito 2012; Sá et al. 2014; Silvestre and de Brito 2009).

As shown in Table 1, the main anomalies are organized in three groups: aesthetic (AA), which do not jeopardize the integrity of the building but strongly influence its visual appearance; associated with the presence of moisture (AH); and mechanical (AM), which are associated with the concentration of stresses (loads or displacements) that lead to the building's degradation through their physical destruction (Sá et al. 2014). Figure 1 presents some examples of the anomalies observed on the cultural heritage analyzed.

2.2. Classification of probable causes of the anomalies

This study does not intend to describe each cause exhaustively, since there are several causes for each anomaly considered. Instead the main causes are typified into generic groups. This classification comprises two main groups of causes: (i) direct, related with mechanical and environmental actions that lead to the occurrence of defects; and (ii) indirect, related to causes that need a direct cause to trigger the pathological process and comprising execution, and maintenance errors (Garcez et al. 2012a). All the possible causes (direct and indirect) of these anomalies (totalizing 31 causes) were then classified into five groups (Table 2): (a) design and execution errors (with the designation CA); (b) external mechanical actions (with the designation CB); (c) environmental actions (with the designation CC); and (d) use and maintenance actions (with the designation CD).

2.2.1. Design and execution errors

Design and execution errors are responsible for a large number of pathological situations, mainly due to the result of unskilled workmanship and the subcontracting of the majority of construction works (Garcez et al. 2012a). Also, the inappropriate selection of the materials, their own vulnerability and consequently their poor in-use performance (Ahzahar et al. 2011; Delgado et al.

Table 1. Proposed classification of the main maintenance source elements of parish churches.

Designation Element	Group of anomalies	Element	Anomaly
AA1	Aesthetic anomalies	*t*	Scratches or wrinkles
AA2	Aesthetic anomalies	*t, r, mc*	Stains/Color change/Discolouration
AA3	Aesthetic anomalies	*r, mc*	Accumulation of debris and superficial dirt
AH1	Anomalies associated with humidity	*t, r, mc*	Biological colonization, e.g., fungi or xylophage insects
AH2	Anomalies associated with humidity	*t, mc*	Detachment/Loss of adherence
AH3	Anomalies associated with humidity	*r*	Corrosion
AH4	Anomalies associated with humidity	*m, mc*	Efflorescence/cryptoflorescence or carbonation
AM1	Mechanical anomalies	*m, t, r, f, mc*	Cracking/fractures
AM2	Mechanical anomalies	*m, t, r, mc*	Crumbling/Disintegration/Disaggregation
AM3	Mechanical anomalies	*m*	Crushing
AM4	Mechanical anomalies	*m*	Bulging
AM5	Mechanical anomalies	*m*	Degradation of the mechanical characteristics
AM6	Mechanical anomalies	*m*	Failure to comply with thermal and acoustic requirements
AM7	Mechanical anomalies	*t*	Warping, swelling, or other flatness deficiencies
AM8	Mechanical anomalies	*t, r*	Broken or splintered elements/Spalling/Exfoliation
AM9	Mechanical anomalies	*t*	Rot
AM10	Mechanical anomalies	*r*	Misalignment of cladding elements/Insufficient slope
AM11	Mechanical anomalies	*f*	Insufficient structural sections
AM12	Mechanical anomalies	*f*	Deformation and differential movements
AM13	Mechanical anomalies	*f*	Collapse
AM14	Mechanical anomalies	*r*	Lack of downspouts and drain nozzles
AM15	Mechanical anomalies	*r*	Absence of fastening elements

Note: m refers to masonry; *t* to the timber elements; *r* to roofs; *f* to foundations; and *mc* to mortars and claddings

Figure 1. Examples of anomalies observed in the built heritage and its classification.

2013) lead to the occurrence of a large number of anomalies. Chew, Tan, and Soemara (2004) refers that the selection of materials, in terms of their durability, is extremely relevant in order to control the occurrence of buildings' defect.

2.2.2. External mechanical actions

External mechanical actions (CB1–CB8) include a great variety of causes, namely: impacts; vibrations; differential movements; shrinkage or swelling of elements; and accidental actions, such as vandalism. As mentioned by

Table 2. Proposed classification of the causes of anomalies in built heritage.

Classification of the main probable causes	
CA	**Design and execution errors**
CA1	Incompatible, omitted, or unsuitable choice of materials
CA2	Lack of support preparation (cleaning, roughness, wetness)
CA3	Inadequate application of joints
CA4	Setting of warped or defective timber elements
CA5	Lack of conformity to design
CA6	Disregard of the settling time between the stages of execution
CA7	Corrosion in metal elements
CA8	Incorrect design/detailing of the elements
CA9	Inexperienced or poorly qualified workmanship
CA10	Incorrect positioning of the different layers
CB	**External mechanical actions**
CB1	Stress concentration
CB2	Shrinkage or expansion
CB3	Impacts/Bumping
CB4	Actions not foreseen at design stage
CB5	Abrasion
CB6	Structural movements and differential settlements
CB7	Stress concentration
CB8	Land conditions/Characteristics of the ground soil
CC	**Environmental actions**
CC1	Solar radiation/Temperature action
CC2	Presence of damp
CC3	Wind/Rain action
CC4	Atmospheric pollution
CC5	Poor ventilation
CC6	Natural wear and tear
CD	**Use and maintenance actions**
CD1	Lack or inadequate maintenance
CD2	Plumbing defects/Lack of fittings (piping, drains, gutters, rainwater vertical piping)
CD3	Premature use
CD4	Accidental actions and vandalism
CD5	Change of the initially predicted in-service conditions

Delgado et al. (2013), depending on their severity, these actions can lead to cracking, breaking, or splintering of the timber elements.

2.2.3. Environmental actions

Environmental actions (CC1–CC6) strongly influence the conservation state of buildings, being the main causes of anomalies in heritage buildings, especially the combined action of rain and wind, accelerating existing pathology. Strong winds can cause the detachment of cladding elements, especially in steep-pitched roofs, with incorrectly placed or degraded elements, or with unfastened elements (Guirguisa, Abd El-Aziz, and Nassief 2007; Pinto, Varum, and Ramos 2011). Moreover, the environmental actions are also responsible for colour changes in the external claddings (Garcez et al. 2012a).

The severity of these actions depends on the degree of exposure of the buildings and their elements and the intensity of the individual actions. Solar radiation and other atmospheric agents are responsible for chemical changes on the buildings' elements, even though these changes do not jeopardize their mechanical properties. The rain action accelerates this degradation process (Delgado et al. 2013). In fact, the presence of moisture is known as a major cause if the advent of defects in buildings (around 76% of all the defects detected, according to a study performed by Almås et al. (2011)). According to Who (2009), the presence of damp is responsible for 75–80% of the building envelope's defects. There are several ways for moisture to occur, such as: from materials applied wet; from migration through porous materials (e.g., rising damp); from condensation; due to hygroscopic phenomena; due to random causes (e.g., failure of water drainage systems); and in the majority of the cases, due to rainwater, which can penetrate in the building through discontinuities in walls, floors, roofs, windows, and doors (Kubba 2008). In timber elements, common in churches, the occurrence of moisture also affects the buildings durability and usually causes irreversible changes in their mechanical strength (Nunes and Cruz 2003).

This group of anomalies also include biological actions such as the establishment of microorganisms (algae, moss, fungi, lichen, among others), the attack of xylophages and insects, the growth of parasitic vegetation (miscellaneous plants), among other living beings (pigeons and bats).

2.2.4. Use and maintenance actions

The last group of causes (CD1–CD5) comprise actions related to the buildings' use and maintenance, and includes lack of conservation/maintenance, deficient ventilation of inner spaces, and lack of periodic inspections, among others. As mentioned by MacKenzie et al. (2007), maintenance actions allow ensuring that the initial condition of a building element will remain intact, allowing this element to continue successfully performing its projected function. Therefore, the lack of maintenance compromises the durability of the buildings elements, allowing these elements to degrade over time until reaching the end of their service life (Grüll et al. 2011).

On the other hand, an inadequate maintenance can also promote and accelerate the occurrence of defects. The use, during maintenance operations, of materials or technologies different from the existing ones can generate incompatibilities between the different components. Their effects can trigger the appearance of new anomalies, thus contributing to the worsening of the degradation phenomena (Garcez et al. 2012a).

2.3. Anomaly/probable cause correlation matrix

Table 3 presents a correlation matrix between the anomalies and their probable causes (showing anomalies in rows and causes in columns), based on the

Table 3. "Anomaly-cause" correlation matrix for built heritage.

	CA1	CA2	CA3	CA4	CA5	CA6	CA7	CA8	CA9	CA10	CB1	CB2	CB3	CB4	CB5	CB6	CB7	CB8	CC1	CC2	CC3	CC4	CC5	CC6	CD1	CD2	CD3	CD4	CD5
AA1	2	0	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AA2	2	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	2	2	2	0	1	2	2	1	0	0	0
AA3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	2	0	0	0	2	0	2	1
AH1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	2	1	2	1	0	2	0	0	0
AH2	2	2	1	0	1	1	1	0	2	0	1	1	1	1	0	1	1	0	0	2	1	0	0	1	1	1	1	0	0
AH3	1	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AH4	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	2	0	0	0
AM1	0	1	1	0	1	1	0	0	0	1	1	2	2	0	2	2	2	1	1	1	1	0	0	1	0	0	0	2	0
AM2	2	2	0	0	1	1	0	1	1	2	0	2	2	0	2	0	1	0	2	2	2	0	0	1	1	1	0	2	0
AM3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0	0	0	0	0	0
AM4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
AM5	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
AM6	1	0	0	0	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
AM7	0	1	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
AM8	1	0	0	2	0	0	0	1	0	0	1	1	2	1	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0
AM9	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	1	1	0	0	0
AM10	0	0	0	0	2	0	0	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AM11	0	0	0	0	2	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AM12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2	0	0	0	0	0	0	0	0	0	0	0
AM13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0	0	0	0	0	0	0	0	0	0	0
AM14	0	0	0	0	2	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AM15	0	0	0	0	2	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

description shown in Tables 1 and 2. This matrix could be an useful tool for an inspector in situ, since it can help in its diagnosis by giving hints to identify the causes of an anomaly just detected; at the intersection of each row and column, a correlation degree (0, 1, or 2) is determined (Athmani et al. 2015; Carretero-Ayuso, Moreno-Cansado, and Cuerda-Correa 2015; Delgado et al. 2013; Flores-Colen, de Brito, and de Freitas 2008; Garcez et al. 2012a; 2012b; Ruiz-Jaramillo et al. 2016; Neto and de Brito 2012; Othman et al. 2015; Vicente, Ferreira, and da Silva 2015; Sá et al. 2014; Silvestre and de Brito 2009; Suffian 2013; Walter, de Brito, and Grandão Lopes 2005):

- 0—no correlation; there is no direct or indirect relationship between the anomaly and the cause;
- 1—low correlation—indirect (first) cause of the anomaly related to the triggering of the deterioration process; cause not necessary for deterioration to progress; and
- 2—high correlation; direct (near) cause of the anomaly, associated with the final stage of the deterioration process; when one of these causes occurs, it is one of the main reasons for the deterioration process and is essential to its development.

3. Description of the sample

It is extremely important to understand the difference between the detailed approaches used for individual buildings and those methods most efficient for larger scale analysis of groups of buildings, as is the case of this study. However, when increasing the number of buildings and the area to be assessed, the resources and amount of information required also increased, so it is necessary to simplify the building typologies and the anomalies and causes of this kind of constructions, thus reducing the complexity of the analysis.

3.1. A sample of heritage building located on south spain

This study is based on available data regarding the state of conservation of 20 heritage buildings located in the province of Seville, Spain, in an area over 14,000 km^2. The geographical region extends from the Atlantic Ocean (Southeast) until the mouth of the Guadalquivir River (Southwest) (Figure 2). This territory has a warm Mediterranean weather with an annual average temperature of 18.5ºC; winters are generally mild. Nevertheless, in the summertime the temperature

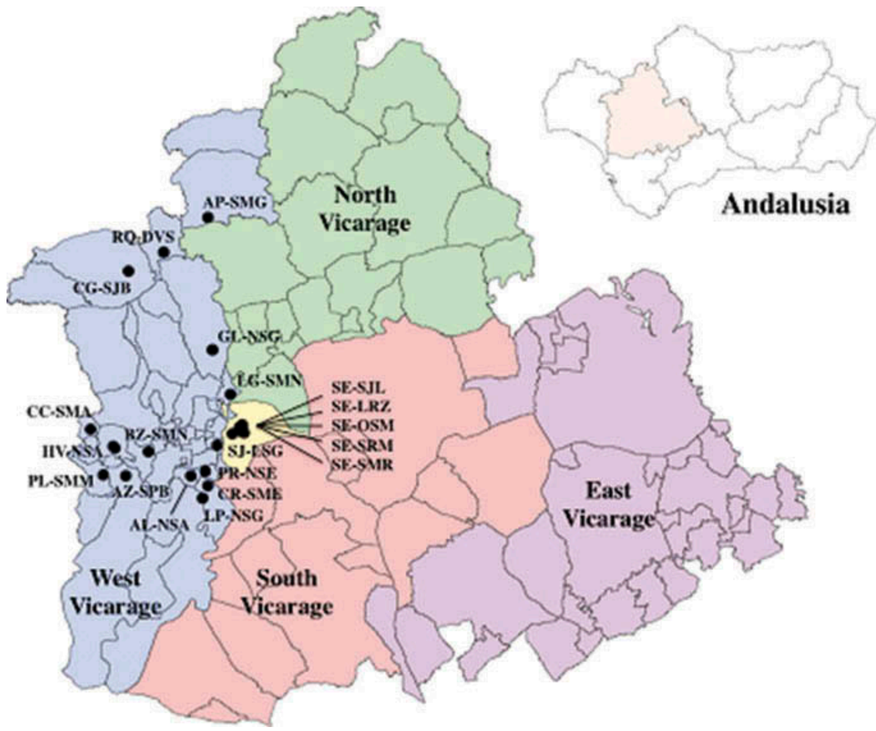

Figure 2. Location of the sample in the Province of Seville, Spain.

often can easily exceed 40ºC. This sample of historical constructions was built in the Mudejar-Gothic, Renaissance and Baroque styles between the 13th and 18th centuries. Most of these churches were built in the Middle Ages and their architectural style was a unique Spanish artistic movement since it was influenced by both Islamic and Gothic Christian elements. These churches are morphologically characterized by this stylistic dualism: a vaulted Gothic apse and a body of three naves with a timber roof (collar beam in the main nave) of Moorish origin. Its brick walls are complemented with quadrangular or sometimes octagonal pillars and with raised brick moldings as decoration. Pointed round or segmental arches rest on these supports. Among other elements of particular interest, funeral chapels have been successively added to the side naves, which on some occasions, are housed in the remaining sections of pre-existing mosques (Zamarreño, Girón, and Galindo 2008). The built heritage buildings under analysis are shown in Figure 3.

3.2. Constructive characterization of the case studies

Table 4 presents the characterization of the 20 churches analyzed, according to their construction time, their architectural style, and some relevant information regarding the main maintenance actions performed over the years. Most of these churches have Gothic-Mudejar architecture with different variations. Other primitive parish churches disappeared and were built in either baroque or neoclassical style after the earthquake of Lisbon (1755). The 20 churches analyzed present similar constructive characteristics. The predominant materials used in the monuments analyzed in the province of Seville were bricks, limestones, mortars, and marbles (Colao et al. 2010). In the Gothic-Mudejar churches there are either stonework or brickwork (in some cases, covered by mortars) as support structure, a horizontal timber covering with jointed rafters, and a finishing consisting of ceramic tiles on top. The foundations are made of continuous footings of bricks or stones. On the columns, the foundations are made of brick or stone footings (Ortiz and Ortiz 2016). The churches analyzed show that the materials used in the constructive system and in the structure are very similar. Nonetheless, it is possible to find other kind of materials as concrete or metal elements introduced into the buildings after interventions or refurbishment actions in the 20th and 21st centuries.

4. Methodology

4.1. Functional service life model

The serviceability of buildings is a complicated system of associations between several variables. The loss or

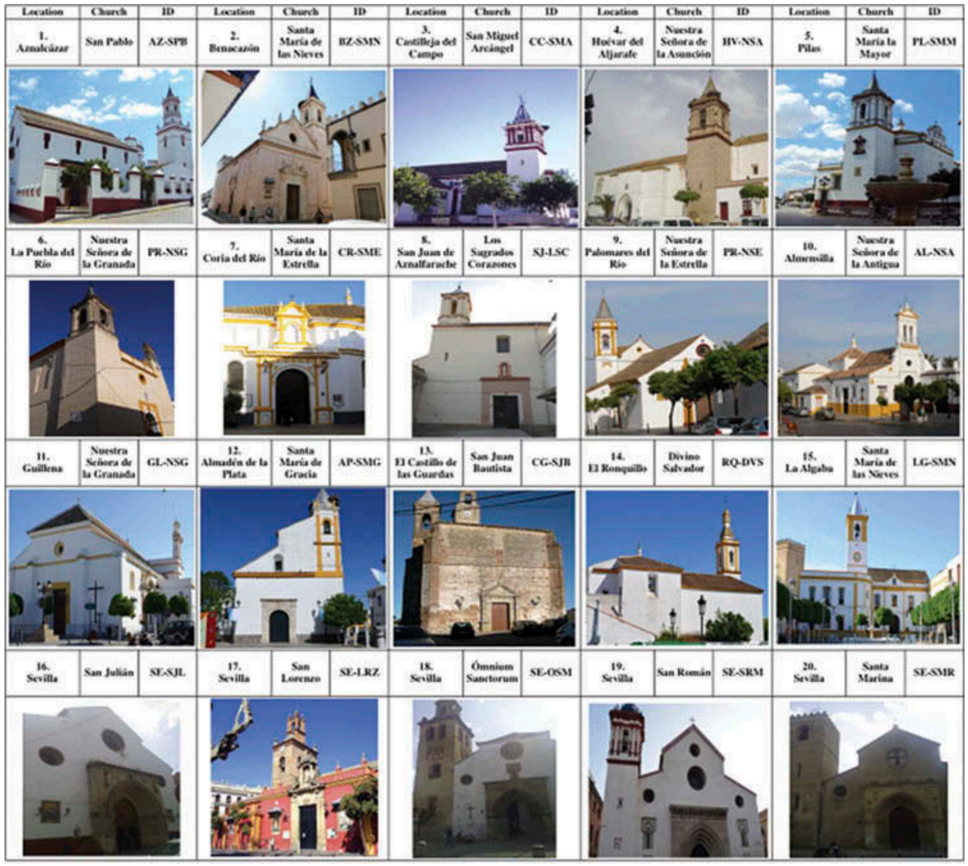

Figure 3. Illustration of the sample of heritage buildings analyzed.

gain of functionality of the heritage constructions, related with the refurbishment and maintenance actions over time, is evaluated. Therefore, different assessments of the input parameters are possible and, in some situations, traditional logic is unable to lead to unequivocal conclusions (Prieto et al. 2016b). Thus, the principles of fuzzy logic established by Zadeh (1965) were used. This fuzzy inference system (FIS) identifies a total of 17 input parameters. In Table 5 the sample of input variables is defined.

4.1.1. Fuzzification

The fuzzification process comprises the transformation of crisp values into grades of membership for linguistic terms of fuzzy sets. Input variables may be translated into linguistic terms, such as *Very Good, Good, Regular, Bad, or Very Bad*. The membership functions are used to associate a grade to each linguistic term (Silva, De Brito, and Gaspar 2016).

These applications assign a degree of membership to each element in the discourse universe U on which the fuzzy set in question is defined. The membership function $\mu_A(u)$ of a fuzzy set A can take any value in the range [0, 1] (Equation (1)):

$$\mu_A(u) : \mathrm{U} \to I[0, 1]. \tag{1}$$

Gaussian-type membership functions are generally used, as they are considered the most appropriate for modeling the degradation conditions of the buildings and also because a non-zero value can be reached at all points (Ross 2010). This happens in all membership functions of the fuzzy inference model, except in the input variable v_1: *Geological location*, in this case a trapezoidal function is used.

Each one of the membership functions for the input, intermediate and output variables of the model have a linguistic label associated to them, from the minimum values *EG—Extremely Good* or *VG—Very Good* (very low vulnerability or risk); to maximum values *B—Bad, VB—Very Bad*, or *EB—Extremely Bad* (very high vulnerability or risk).

4.1.2. Knowledge base and inference rules

The degradation of building components occurs mainly due to the static-structural and anthropogenic damage, weathering and pollution (Ortiz and Ortiz 2016). In this study, the most relevant factors for the deterioration of built heritage are considered in the proposed model. The full hierarchical structure of the fuzzy

Table 4. Characterization of the 20 churches analysed.

ID	Parish church	Location	Construction time	Architectural style	Information and time of the more relevant maintenance actions performed
AZ-SPB*	San Pablo	Aznalcázar	15^{th} Century (1400)	Mudejar-Gothic	1765–1767—Generalized rehabilitation of the church. 1932—The temple has been torched, losing the roofs of the naves, the altarpieces and the images that enhanced the beauty of this interesting building. 1945—The new church was opened, being a replica of the previous one. Several artworks only were replaced over the subsequent years. 2003–2004—Periodic visual inspections, in order to avoid the presence of water in the church. Repainting of the external wall and execution of a waterproofing layer in the vaults of the presbytery. 2005—Reinforcement of the timber beams in the roof, due to termite attack.
BZ-SMN*	Santa María de las Nieves	Benacazón	16^{th} Century (1550)	Mudejar-Gothic	1632–1634—Reform of the altarpiece. 1650—Another nave and a Sagrario chapel are added to the rectangular nave. 1760—After the Lisbon's earthquake, the building is repaired, which allow building the tower (two bodies, with pyramidal spire), the dressing room and windows' covers.
CC-SMA*	San Miguel Arcángel	Castilleja del Campo	18^{th} Century (1760–1762)	Baroque	1696—It was declared the necessity of intervene in the church 1723—Execution of the first rehabilitation actions. 1742—Execution of the altar. 1760—After the Lisbon's earthquake, the church is damaged and ruined. Therefore, some actions were performed in order to avoid the collapse of the building and its bell tower. 1762—The new parish church was built. 1905—The wood ladders on the pulpit were replaced by metal ladders. 1917—Replacement of the ceramic tiling floor 1983—Important works were performed for the expansion and renovation of the chapel. 1997—Integral replacement of the roof of the chapel, Sagrario chapel, baptismal chapel, sacristy and storage room. The bell tower is restored, replacing ceramic panels. The walls of the tower have been plastered and repainted, restoring its original style, white and red tile. A generalized cleaning was performed.
HV-NSA*	Nuestra Señora de la Asunción	Huévar del Aljarafe	16^{th} Century (1510)	Mudejar-Gothic	1550—The chapel of the Virgen de la Antigua (also known as the Guzman or Don Gonzalo chapel) was added to the building. 1700—The Sagrario chapel was added to the building. 1760—Reconstruction of the tower bell, destroyed by the Lisbon's earthquake. 1793—A neoclassical altarpiece was built. 1850—Generalized rehabilitation actions. 1919—The church presented a severe degradation condition, being subjected to eight months of rehabilitation works in order to restore its functionality levels. 1920—Reform of the crypt. 2012—Restoration of the church
PL-SMM*	Santa María la Mayor	Pilas	16^{th} Century (1575)	Mudejar-Gothic	1618—Expansion works. 1712 /1717 /1728–1731—Rehabilitation works. 1775—Expansion of the church. 1798—Execution of the altarpiece.
LP-NSG*	Nuestra Señora de la Granada	La Puebla del Río	13^{th} Century (1275)	Mudejar-Gothic	1475—Change in the direction of the axis of the temple. 1560–1585—Expansion of the church. 1618 /1627—Maintenance works, repair of the roof, the vaults and the slabs graves. 1711–1716—Repair of walls. 1755—Rebuild of the tower's roof. 1846–1899—Maintenance works, cleaning of the roof elements and repainting of the walls. 1905–1939—Generalized maintenance works, on the roof, porches and masonry. 1988–1989—Works in the upper body of the building, restoration of the heads of the beams of the choir.
CR-SME	Nuestra Señora de la Estrella	Coria del Río	14^{th} Century (1350)	Mudejar-Gothic	1598—Suffered a fire, which almost destructed the church (only the head of the church it remains standing). 1620—Rehabilitation of the support structure of the arches of the naves of the church. 1700—Construction of the second body of the tower, the Rosario's Chapel and the Chapel del Carmen. 1750—Reconstruction of the building. 1900—Construction of the chapel del Gran Poder. 1911—Construction of the sacramental chapel, to the right of the head of the temple. 1983—Consolidation and restoration of the apse of the cathedral of Coria del Río. Interventions in the church.

(*Continued*)

Table 4. (Continued).

ID	Parish church	Location	Construction time	Architectural style	Information and time of the more relevant maintenance actions performed
SJ-LSG	Los Sagrados Corazones	San Juan de Aznalfarache	18^{th} Century (1708)	Baroque	1500—The Franciscan monastery which belongs to the church in the half of the century is built. 1708—Date of completion of construction of the temple, which began in 1400. 1800—Construction of the Eucharist and baptismal chapel. 1886—Construction of the chapel-pantheon of Condes de Aguiar. 1940–1948—Building project of monumental complex that are currently part the temple. 2006 /2012 /2013—Generalized maintenance works.
PR-NSE*	Nuestra Señora de la Estrella	Palomares del Río	16^{th} Century (1591)	Mudejar-Gothic	1625—Poor state of conservation of the support structure of the temple. Only in 1650, the rehabilitation works are performed in the support structure. 1696–1698—Rebuilding the reinforcement of the nave. Rehabilitation of the archways of the epistle. Application of a new flooring system. 1746—Generalized maintenance works. 1755–1757—Repair of the damage inflicted by the Lisbon's Earthquake. 1778–1779—Reforms on the front and top of the tower, consolidation of the masonry on roofs and naves. Rehabilitation of timber in the nave of the church, as well as beams and doors. 1902–1905—Generalized rehabilitation works.
AL-NSA*	Nuestra Señora de la Antigua	Almensilla	15^{th} –16^{th} Century (1444–1500)	Mudejar-Gothic	1600—Rebuilding of the parish. 1715 /1716—Rehabilitation of the church. 1775—Generalized renovation works (rebuilding of the church). 1960—The church suffered improved works. 2011—Proposal for intervention on the roofs of the church and other general repairs.
GL-NSG*	Nuestra Señora de la Granada	Guillena	15^{th} –16^{th} Century (1400–1500)	Mudejar-Gothic	1725—Major renovation: change the main altar, the floor cladding and the columns of the altars. 1755—The Lisbon's earthquake probably lead to the fall of a bell tower, which it became impossible to lift. A new steeple for the bells was held. 1960—Demolition of the choir. 2001–2003—The church was closed for major renovations, including the replacement of the tiles elements of the roofs, the walls were rehabilitated, a new floor coating is installed, the sanctuary is restored and new lighting is installed.
AL-NSA	Santa María de Gracia	Almadén de la Plata	16^{th} –17^{th} Century (1575–1600)	Renaissance	1600—Rehabilitation of the roof of the main chapel. 1678—Building of the main facade and belfry. 1975—It is considered that the temple is in poor conservation conditions and in 2002 restoration and conservation actions were performed.
CG-SJB	San Juan Bautista	El Castillo de las Guardas	15^{th} Century (1400)	Mudejar-Gothic	1600–1650—The side chapels, including San Bartolomé chapel were built. 1666—There is a ruin threat regarding the old bell tower, so a new tower was rebuilt. 1700—Reinforcing of the foundations. 1745–1748—Maintenance works. 1975—Rehabilitation works.
RQ-DVS*	Divino Salvador	El Ronquillo	17^{th} Century (1600)	Baroque	1711—Construction of the bell tower. 1713—Rehabilitation of the walls. 1750—It is considered that the temple is in poor conservation conditions, but the rehabilitation of the building only occurs 25 years later. 1850 /1903—The church was in ruins so a major reform occurs.
LG-SMN*	Santa María de las Nieves	La Algaba	14^{th} –15^{th} Century (1370–1400)	Mudejar-Gothic	1405–1500—Construction of the bell tower. 1756–1768—The Lisbon's earthquake lead to the ruin of the church, therefore, the church was rebuilt, creating the side chapels existing today. 2004—The tiles of the chapels are restored as well the presbytery. 2014—Restoration of the steeple of the church.
SE-SJL*	San Julián	Sevilla	14^{th} –15^{th} Century (1300–1407)	Mudejar-Gothic	1700—Generalized maintenance works. 1800—The building suffered a several damage due to the Lisbon's earthquake, being necessary to repair the church, and a reconstruction of the tower bells. 1932—The church was burned, only remaining the walls and the columns. 1946—It ends to restore the temple after the previous fire (in 1932). 1997—Rehabilitation of the building.

(*Continued*)

Table 4. (Continued).

ID	Parish church	Location	Construction time	Architectural style	Information and time of the more relevant maintenance actions performed
SE-LRZ*	San Lorenzo	Sevilla	14th Century (1300–1399)	Mudejar-Gothic	1738—Expansion of the chapel of Divina Pastora. 1800—The building is modified, changing the quite primitive style of the church, such as the vault of average orange on decorations above the chancel and choir stalls. 1877—The body of the church is transformed. 1950—Rehabilitation actions, mainly on roofs and walls.
SE-OSM*	Omnium Sanctorum	Sevilla	13th Century (1250–1399)	Mudejar-Gothic	1300—Reinforcement of the vaults (which belong to the fourteenth century). 1965—Rehabilitation of the tower. 1991–2001—Generalized maintenance works. Replacement of the roofs and ornamental elements. Rehabilitation of the foundations of the tower, due to the presence of differential settlements.
SE-SRM	San Román	Sevilla	14th Century (1356–1399)	Mudejar-Gothic	1400—Rehabilitation and maintenance works. 1702—Repair of the roofs and other parts of the building. 1948—General rehabilitation of the building, in order to restore its function, after the fire of 1936. 1976—Rehabilitation of the roof. 1991—Total renovation of the church, being closed until 2004.
SE-SMR*	Santa Marina	Sevilla	14th Century (1356)	Mudejar-Gothic	1700—Rehabilitation of the chapels. 1725—Repair works to solve humidity problems and for repair roofs and other pathological situations detected in the main naves. 1755—Rehabilitation of the church to improve its functionality after the Lisbon's Earthquake. 1869—Reconstruction of the chapel after a fire. 1906—Reconstruction of the baptismal chapel, reproducing the chapel of Santísimo Sacramento. 1936—The church was burned, remain in ruins for almost 30 years and leave it unused until 1981. 1994—Reconstruction of the church.

* Affected by the Lisbon's Earthquake (1755)

Table 5. Fuzzy model input factors and description (Prieto et al. 2016b).

ID	Factors	Description of possible valuation
Vulnerability		
v_1	Geological location	Optimum/acceptable/unfavorable ground conditions in terms of stability.
v_2	Roof design	Fast/normal/complex and slow evacuation of water.
v_3	Environmental conditions	Buildings 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.
Static-structural risks		
r_6	Load state modification	Apparently/symmetric and balanced/disorderly modification.
r_7	Live loads	Live load below/equal/higher than the original level.
r_8	Ventilation	Natural cross-ventilation in all or only in some areas.
r_9	Facilities	All/some facilities are in use or they are not ready to be used.
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 risks		
r_{12}	Rainfall	Area with low/medium/maximum annual rainfall.
r_{13}	Temperature	Area with low/medium/maximum temperature differences
Anthropic risks		
r_{14}	Population growth	Population growth greater than 15%/0%/less than 5%.
r_{15}	Heritage value	Properties with great/average/low historical value.
r_{16}	Furniture value	Social, cultural and liturgical appreciation (high/average/low value).
r_{17}	Occupancy	High/media/low occupancy in the building.

model is shown in Figure 4, where it is possible to see the interrelation between the variables developed in the different levels of the fuzzy model. To establish these rules in the model, the following documents were analyzed: Spanish Technical Building Code (2007); National Cathedral Plan (1990); Law on Construction Planning; Heritage Conservation Network (2007); UNE 41805:2009 IN (2009); ISO 15686.

Also, the fuzzy rules applied to quantify the functionality of the churches analyzed are quantified and validated through an experts' survey, comprising a group of 15 professionals with expertise in the

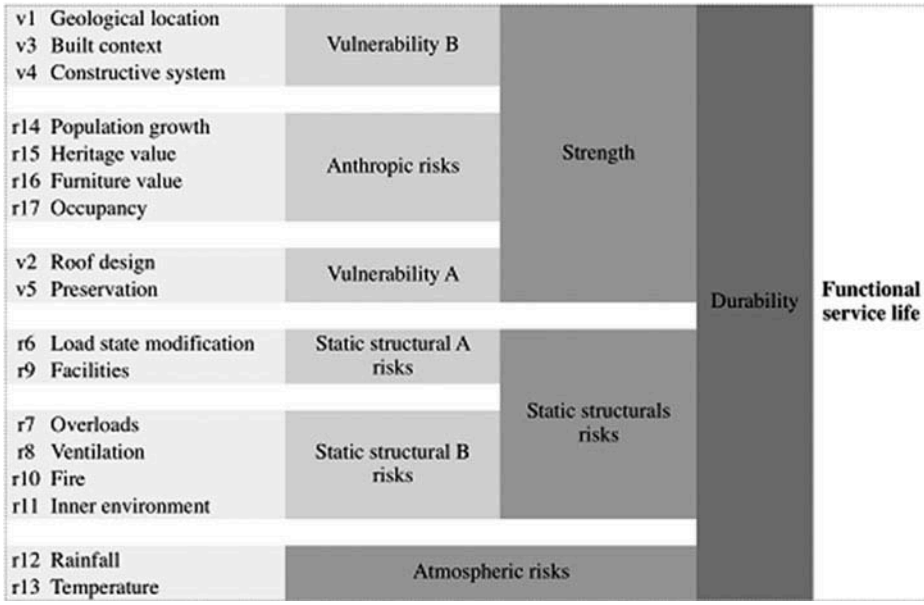

Figure 4. Hierarchical structure of the fuzzy expert system (data sourced from Macías-Bernal, Calama, and Chávez 2014).

Table 6. Profiles of the professional experts' survey.

2	Teachers of Rehabilitation and Pathology
2	Fireman commanders—from Seville and Madrid
1	Manager of a construction company
1	Director of an accredited laboratory of building materials
1	Restoration artist
1	Architect
1	Technical architect
1	Archaeologist
1	Head of the building maintenance sector of the municipality of a province capital of 700,000 inhabitants
1	Director of a World Heritage conservation building
1	Person in charge of the conservation of a Port Authority
1	Director of an insurance company at international level
1	Expert in quality management in buildings, with numerous publications on this subject

Note: All professional experts with over 20-year recognized experience

management of built heritage. A Delphi methodology, through the Opina software (2004) property of University of Seville, was used to obtain all the results and conclusions from the expert's survey, which have been consulted in the model's design stage (Macías-Bernal, Calama, and Chávez 2014). In Table 6 the main professional expert's profile is described.

The core of a fuzzy system is the knowledge base comprised of two components: the database and the rule base. This step is the principal part of a fuzzy expert system that combines the facts derived from the fuzzification process with the rule base generated previously and carried out in the modelling process. The methodology uses the fuzzy if-then rules to assign a map from fuzzy inputs to fuzzy outputs based on fuzzy composition rules. The "if-then" fuzzy rules set, as well as its hierarchical structure.

Mamdani's fuzzy model, one of the most accepted algorithms, is used in this methodology (Mamdani and Assilian 1975), which consists of fuzzy rules where each rule describes a local input-output relationship.

The base rule is a collection of fuzzy control rules, comprising linguistic labels, representing the expert knowledge of the controlled system. The fuzzy logic inference model, known as a generalized modus ponens, is established in the FBSL model, Equation (2), together with its hierarchical structure. The min-max or Mamdani inference mechanism is used in the composition of fuzzy propositions. Unlike in a conventional expert system, in a fuzzy system, various rules can be activated simultaneously. This type of method works with the minimum operator as the implication function and the maximum as the aggregation operator (Ross 2010):

$$\text{Rule (j)} : \text{IF } v_1 \text{ is } A_1{}^j \text{ AND } v_2 \text{ is } A_2{}^j \ldots v_n \text{ is } A_n{}^j \text{ THEN } y \text{ is } B^1, \tag{2}$$

where $v_i(x)$ are the input (output) linguistic variables, A_i^j (B) are the linguistic labels used in the input (output) variables, n is the inputs numbers and j rules numbers.

All the fuzzy rules are extracted from engineering and architect knowledge, expert's judgments and experience (Prieto et al. 2016a). The full hierarchical structure of the fuzzy model is shown in Figure 4, where it is possible to clearly see the interrelation of the variables developed in the different levels of the fuzzy model.

As seen in Figure 4, the first level of intermediate fuzzy variables on the hierarchical structure is the next one. For *Vulnerability A (Va), Vulnerability B, Static-*

Table 7. "If-then" fuzzy rules generated by a group of professional experts.

Rule number	Fuzzy proposals *"if-then"*		
Rule 1	If (v_2 is *VG*)	And (v_5 is *VG*)	Then (*Va* is *VG*)
Rule 2	If (v_2 is *VG*)	And (v_5 is *G*)	Then (*Va* is *G*)
Rule 3	If (v_2 is *VG*)	And (v_5 is *R*)	Then (*Va* is *R*)
Rule 4	If (v_2 is *VG*)	And (v_5 is *B*)	Then (*Va* is *B*)
Rule 5	If (v_2 is *G*)	And (v_5 is *VG*)	Then (*Va* is *VG*)
Rule 6	If (v_2 is *G*)	And (v_5 is *G*)	Then (*Va* is *G*)
Rule 7	If (v_2 is *G*)	And (v_5 is *R*)	Then (*Va* is *R*)
Rule 8	If (v_2 is *G*)	And (v_5 is *G*)	Then (*Va* is *B*)
Rule 9	If (v_2 is *R*)	And (v_5 is *VG*)	Then (*Va* is *G*)
Rule 10	If (v_2 is R)	And (v_5 is *G*)	Then (*Va* is *R*)
Rule 11	If (v_2 is *R*)	And (v_5 is *R*)	Then (*Va* is *B*)
Rule 12	If (v_2 is *R*)	And (v_5 is *B*)	Then (*Va* is *VB*)
Rule 13	If (v_2 is *B*)	And (v_5 is *VG*)	Then (*Va* is *R*)
Rule 14	If (v_2 is *B*)	And (v_5 is *G*)	Then (*Va* is *B*)
Rule 15	If (v_2 is *B*)	And (v_5 is *R*)	Then (*Va* is *VB*)
Rule 16	If (v_2 is *B*)	And (v_5 is *B*)	Then (*Va* is *VB*)

Structural A risk, *Static-Structural B risk-B*, and *Anthropic risk* these variables are generated by inference rules based on the entry variables (e.g., v*ulnerability A* is generated through 16 diffuse rules involving the variables: *Roof design* (v_2) and *Preservation* (v_5)—see Table 7).

After the second level is arranged, the input variables are grouped in each new level as shown, generating the next output level. In this sense, *Vulnerability A* (*Va*), *Vulnerability B*, and *Anthropic risks* arrange *Strength* in the second rule level. Moreover, *Vulnerability A* (*Va*), *Static Structural A risks*, and *Static Structural B risks* generate the *Static-Structural risk* output.

Finally, the third level made up by *Strength, Static-Structural risk*, and *Atmospheric risk* generates the next *Durability* output, and through this intermediate output and through the 66 inference rules of this level, the level of functionality is obtained as the final output (*FBSL*) (Macías-Bernal, Calama, and Chávez 2014; Prieto, Macías-Bernal, and Chávez 2015).

4.1.3. Defuzzification

The proposed model leads to a functional index of the churches analyzed, based on the if-then rules proposed by the expert survey, thus providing the hierarchical scale of the priority of intervention in the sample analyzed. This mathematical methodology represents imprecise knowledge where uncertainty is present, adding the application of expert experience to the simulation of human reasoning. This system was developed using probabilistic estimation in the fuzzification stage, by translating linguistic labels that describe the assessment in which the input factors are represented by membership functions. The defuzzification stage as serviceability of the buildings is established (output). This model is implemented in the software Xfuzzy 3.0 (1997–2003) (developed by the University of Seville and the IMSE-CNM—Seville Institute of Microelectronics and National Microelectronics Centre).

Finally, the defuzzification step is used to obtain a (crisp) value representing the fuzzy information produced by the inference. The *FBSL* system uses the *center of the area* (COA), i.e., it uses the center of the area of fuzzy set *B* as a proxy value, *FBSL* (Moreno-Velo et al. 2007), which is one of the most common and successful methods for defuzzification processes. The most notable properties of this method are that it is continuous, which means that a small change in the inputs does not imply an abrupt change in the outputs. Its discrete version can be interpreted as a Riemann sum (Equation (3)). The output of the fuzzy model due to convenience is often interpreted by the same acronym that defines the fuzzy model (*FBSL*):

$$FBSL = \frac{\sum_i \mathrm{y_i} çdot \mu_B(y_i)}{\sum_i \mu_\mathrm{B}(\mathrm{y_i}).} \tag{3}$$

The functional service life model (*FBSL*—Fuzzy Building Service Life) is able to manage the risks and vulnerabilities affecting historic architectural sets. This methodology has been enriched throughout the analysis of the international standard ISO 31000:2009 (2009) and the European standard EN 31010:2011 (2011). Both are main reference standards in the field of risk management and assessment in terms of preventive conservation of built heritage (Prieto et al. 2016a). This system has also been correlated with another predictive model that evaluates the physical service life or degradation of building components, showing, as expected, that there is a strong correlation between the functional and the physical service life of buildings. In fact, when the degradation of the building components increases, their functionality index decreases (Prieto et al. 2016b).

4.2. Historical Data

In this work, historical time series data were gathered manually from the parish archives owned by the Archdiocese of Seville and from a company specialized on the sector (Archives of Archdiocese of Seville 2016). The data incorporate: interviews; documents and evidences, included in organizational strategic plans; annual reports; preservation surveys; and budget files. These data include, in some cases, semi-structured interviews with the key stakeholders (decision-makers responsible for the maintenance operations) of the sample of buildings under analysis. Fieldwork observations enabled a deeper understanding of the built environment, historical resources, and property conditions. Therefore, some information has been collected during an extensive fieldwork (performed by Carmona (2014), García (2014), Charneco (2014) and López (2015)), in order to analyze (based on time series) the main factors that influence the functional service life of parish churches in South Spain.

The data achieved cover historical buildings information related with different kind of interventions (maintenance actions, refurbishment, or rehabilitation) from the 13th century until the 21st century (Prieto, Macías-Bernal, and Chávez 2015). Based on 390 records obtained on 20 churches, this study discusses the pathology of buildings according to the main elements of the religious buildings analyzed.

The historical data records also allow determining the functionality index (*FBSL*) over time, evaluating the functional performance of buildings. Recently, Prieto et al. (2016c) applied the FIS and the Delphi method to obtain quantitative results, from qualitative data. This approach provides output data on the functional performance condition of each building at each moment in time whenever information records are available. The Delphi Method is used to eliminate experts' subjectivity, establishing a FDM-type (Fuzzy Delphi Method) assessment methodology that effectively quantifies the service life of buildings over time. This information is crucial for the definition of future preventive conservation plans (Carter and Bramley 2002).

5. Application of the functional service life model by historical time series' recovery

The study of service life over time enables a more rational use of resources, since the information obtained can be incorporated into maintenance management procedures in terms of reference intervals for regular inspection and maintenance actions (Dias et al. 2014). Currently, in European countries, there is an ever-increasing number of properties or areas protected due to their cultural heritage interest (Pickard and Pickerill 2002). The main priority in these kinds of approach is to minimize the anomalies-related risks that influence the functional deterioration of cultural heritage over time (Ipekoglu 2006).

The approach proposed in this study is to evaluate the level of functionality (state of the buildings' performance) based on historical reports recovered over time. Based on this information, the *FBSL* methodology ranks the buildings in three functional degradation conditions: "good"; "medium"; and "bad" (Table 8). In Prieto et al. (2016b), the functionality index is established as a criterion for maintenance planning, revealing that if a building presents an *FBSL* index lower than 34 points, the functional performance of building it is not guaranteed (Table 8). In this sense, an intervention should be considered, as soon as possible in terms of preventive actions to extend the functional service life of buildings. In fact, in the 390 records in a sample of 20 parish churches, every time the functionality index reaches values below the 34 points, a restoration action is performed in the next 5–10 years.

Unusual events (such as wars, earthquakes, fires, and floods) can have a catastrophic impact on the conservation of cultural heritage buildings (Indirli et al. 2003; Ortiz et al. 2014). Löfsten (2000) refers that unexpected singular events are usually followed by a significant increase in conservation and maintenance costs with respect to the last preventive maintenance work carried out.

Maintenance actions usually occur based on programmatic criteria, being influenced by users' perception and economic constraints (Flores-Colen and de Brito 2010). After a disastrous event, the churches present an unacceptable functionality level, due to the failure of the buildings elements, thus requiring an urgent corrective intervention. In the sample analyzed, the stakeholders usually recognize the urgency of restoring the built heritage after a cataclysm, since in 85% of the buildings under analysis, the time of refurbishment actions after a disastrous event was between 1 and 20 years and only in 3 case studies the refurbishment or rehabilitation delay was higher than 45 years.

Table 9 presents the performance of the 20 case studies analyzed, showing the buildings' serviceability over time. Under normal conditions, the functionality index of the buildings analyzed varies between "good" and "medium". However, the occurrence of unpredictable events usually leads to a minimum *FBSL* index, corresponding to a "bad" functional condition. The data gathered from the sample of the 20 buildings only consider two disastrous events: (a) the Lisbon's earthquake (in 1755) and (b) the Spanish Civil War (in 1936).

Lisbon's earthquake influence decreased the functionality of the heritage buildings considered in this study. Nevertheless, only two buildings present unacceptable serviceability levels. The main consequences of this event were related with the failing of the tower bells, destroying the roofs and support structure (timber elements), and in some cases the candles inside the parish churches caused a fire (Carmona 2014; Charneco 2014).

Table 8. Building performance level (*FBSL*).

Functionality level	Range	Description	Illustrative example	
Good	100 ≥ *FBSL* ≥ 74	Buildings with good serviceability conditions		*FBSL* = 87 San Miguel Arcángel Castilleja del Campo (in 2016)
Medium	74 > *FBSL* ≥ 34	Building requires periodical inspections, in order to maintain an acceptable level		*FBSL* = 57 San Juan Bautista El Castillo de las Guardas (in 2016)
Bad	34 > *FBSL* ≥ 0	Inacceptable serviceability level		*FBSL* = 21 San Julián Sevilla (in 1936)

Table 9. Historical performance levels in 20 parish churches records: 1755; 1936; 2016.

			1755		1936		2016	
ID	Parish church	Location	*FBSL*	Performance	*FBSL*	Performance	*FBSL*	Performance
AZ-SPB	San Pablo	Aznalcázar	42	Medium	**27**	**Bad**	91	Good
BZ-SMN	Santa María de las Nieves	Benacazón	40	Medium	54	Medium	91	Good
CC-SMA	San Miguel Arcángel	Castilleja del Campo	**32**	**Bad**	53	Medium	87	Good
HV-NSA	Nuestra Señora de la Asunción	Huevar del Aljarafe	61	Medium	83	Good	82	Good
PL-SMM	Santa María la Mayor	Pilas	57	Medium	76	Good	79	Good
LP-NSG	Nuestra Señora de la Granada	La Puebla del Río	42	Medium	77	Good	82	Good
CR-SME	Nuestra Señora de la Estrella	Coria del Río	57	Medium	**33**	**Bad**	71	Medium
SJ-LSG	Los Sagrados Corazones	San Juan de Aznalfarache	61	Medium	59	Medium	77	Good
PR-NSE	Nuestra Señora de la Estrella	Palomares del Río	47	Medium	58	Medium	66	Medium
AL-NSA	Nuestra Señora de la Antigua	Almensilla	55	Medium	66	Medium	66	Medium
GL-NSG	Nuestra Señora de la Granada	Guillena	59	Medium	58	Medium	65	Medium
AP-SMG	Santa María de Gracia	Almadén de la Plata	66	Medium	37	Medium	73	Medium
CG-SJB	San Juan Bautista	El Castillo de las Guardas	67	Medium	36	Medium	57	Medium
RQ-DVS	Divino Salvador	El Ronquillo	65	Medium	64	Medium	72	Medium
LG-SMN	Santa María de las Nieves	La Algaba	**27**	**Bad**	64	Medium	66	Medium
SE-SJL	San Julián	Sevilla	40	Medium	**21**	**Bad**	80	Good
SE-LRZ	San Lorenzo	Sevilla	56	Medium	69	Medium	77	Good
SE-OSM	Ómnium Sanctorum	Sevilla	58	Medium	**22**	**Bad**	69	Medium
SE-SRM	San Román	Sevilla	54	Medium	**22**	**Bad**	76	Good
SE-SMR	Santa Marina	Sevilla	41	Medium	**20**	**Bad**	76	Good

The Spanish Civil War had also clear consequences on the performance of the religious buildings, since 40% of the sample of buildings considered were burned during this period. Fire in the churches is one serious risk, considered in the fuzzy model to establish the functionality of these buildings, with severe consequences, and may even cause de buildings' destruction (Carmona 2014; Charneco 2014; García 2014; López 2015).

5.1. Application of the methodology to a case study: Santa Marina's parish church

To illustrate the evaluation of the functionality of buildings and their pathology over a long period of time, a case study is analyzed. The following example presents the detailed study of a specific parish, based on the historical time records retrieved from the 13th century

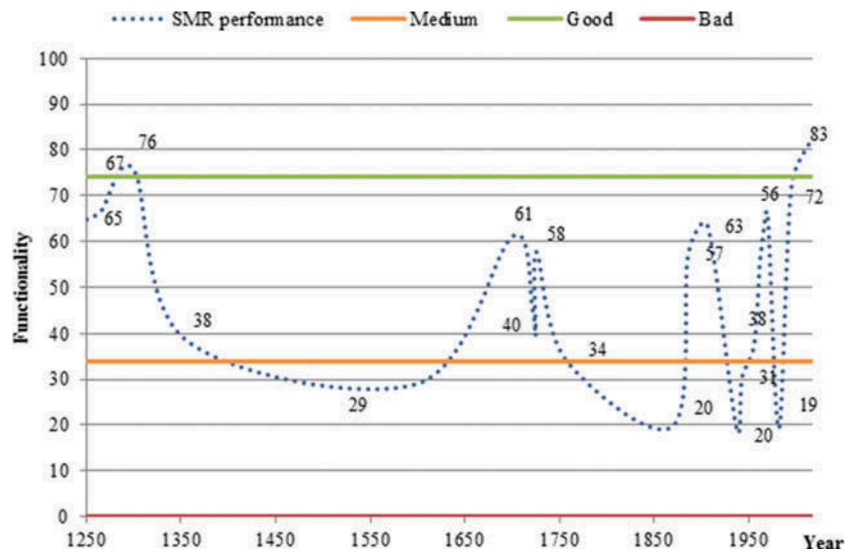

Figure 5. Functional performance over time of Santa Marina's church.

until 2016. In the analysis of Santa Marina's church, (ID code: SE-SMR) a total of 23 historical records were recovered (López 2015). Figure 5 shows the evolution of the Santa Marina church's functionality. Four cataclysm events with disastrous consequences in the building performance were examined: (i) the first one occurred in the 14th century, due to the 1356's earthquake, located around San Vicente's cape, leading to "bad" functional condition of the church; (ii) the second one, occurred in 18th century (1755—Lisbon's earthquake); (iii) the third one occurred in 1936 (first half of 20th century), during the Spanish Civil War, in which the church was burned; and (iv) finally, the fourth event occurred in 1981 (second half of 20th century), corresponding to the complete destruction of the church due to a fire. The building was also involved in another fire during the period of time considered.

Regarding the evaluation of the parish church performance (Table 10 and Figure 5), the data gathered from historical records of Santa Marina's church were considered. The historical records mentioned the following (Vigil-Escalera Pacheco 1991): The building was burned in 1936, during the 60th decade various restoration campaigns (reinforcement of vaults and arches, roofs and masonry reconstruction) were carried out. In 1973, the church was again ready to be opened to the public. However, it remained closed without maintenance actions for almost ten years, even suffering plundering of many of the goods that were stored inside. In 1981, the church suffered another fire. The building did not have any detection or fire protective system and the roof was completely destroyed. Between 1981 and 1994, the reconstruction of the church was performed. During this period: in 1984, emergency works occurred mainly to clear parasitic vegetation on the roofs, in addition to repairing; in 1987 the church reopened after a new restoration project; in 1989 the reconstruction of the coffered ceiling of the central nave was made as well the repair of the decks and in the tower; and, finally, in 1994 the reconstruction works were finalized.

Table 9 presents the quantification of the variables introduced into the fuzzy system, which were defined based on time-series analysis of the historical data, which provide relevant information regarding the vulnerabilities and risks of the building over its life cycle. This quantification is based on an expert knowledge system, as described in this study. When the professional experts, who are analyzing the historical data and quantifying the input variables, cannot find records related with the state of conservation of the building, they must evaluate the building considering an average situation. In this case study, some input variables are considered with the same value during the period of time considered—v1, r12, and r13—since the geological location (v1) remains the same over the years, as well the atmospheric risks, which are considered in a medium level, since the building is located in a Mediterranean climate (with moderate weather conditions).

After the analysis of these historical records, the roof of this church is shown as one of the most vulnerable elements, conditioning the maintenance actions performed, or in other words, the maintenance actions occur mainly to repair and restore the roof of the church.

Table 10. Santa Marina's parish (SMR) historical records from 1250–2016.

Records	Year	Qualitative information	v1	v2	v3	v4	v5	r6	r7	r8	r9	r10	r11	r12	r13	r14	r15	r16	r17	FBSL	Serviceability
1	1250	The parish church is built.	1	3	3	3	2	2	3	3	2	4	3	3	3	4	5	5	3	65	Medium
2	1265	The side chapels are constructed.	1	2	2	3	2	2	3	3	2	4	3	3	3	4	3	3	3	67	Medium
3	1300	The tower and the central body of the building are built. The main front door of the feet is erected.	1	2	2	2	2	2	3	3	2	3	3	3	3	4	4	4	3	76	Good
4	1356	Damages due to the earthquake of 1356.	1	5	4	4	5	4	4	3	3	5	3	3	3	4	5	4	4	38	Medium
5	1600	The church presents generalized deterioration.	1	6	6	6	6	4	4	3	3	5	3	3	3	4	5	4	4	**29**	**Bad**
6	1700	Several chapels are rehabilitated.	1	3	3	3	3	3	4	3	4	3	3	3	3	4	3	3	3	61	Medium
7	1721	Moisture problems on parish's roof.	1	4	4	3	4	3	4	4	4	4	3	3	3	4	4	4	3	45	Medium
8	1724	Report, two chapels need conserved actions.	1	5	4	4	5	4	4	4	4	4	4	3	3	4	5	5	3	40	Medium
9	1725	Maintenance works.	1	3	3	3	3	3	3	3	3	4	3	3	3	3	4	4	3	58	Medium
10	1755	The Lisbon earthquake causes cracks and fractures that lead to repair the damage caused.	1	6	4	4	6	4	4	4	4	4	4	3	3	4	4	4	5	**34**	**Bad**
11	1869	The roofs of the naves are destroyed by a fire. The buildings present a bad conservation state.	1	8	4	4	6	4	7	4	5	4	5	3	3	4	4	4	7	**20**	**Bad**
12	1885	New restoration works in the Chapel of Piety are undertaken.	1	3	3	3	3	3	3	3	4	4	4	3	3	3	4	4	3	57	Medium
13	1906	The baptismal chapel is reconstructed.	1	2	3	3	2	3	3	3	4	4	4	3	3	2	4	4	3	63	Medium
14	1936	The roofs of the naves burn; all altarpieces are lost.	1	7	6	6	7	5	5	5	6	6	4	3	3	4	7	7	7	**20**	**Bad**
15	1942	The building is re-erected following the original Gothic pattern.	1	6	6	6	6	4	4	4	5	4	4	3	3	2	6	6	6	**31**	**Bad**
17	1955	A vertical crack appears in the corner between the tower and the wall.	1	5	5	5	5	4	4	4	4	4	3	3	3	2	5	5	5	38	Medium
18	1961	Conservation and restoration works on the interior walls and facades are considered.	1	3	3	3	3	4	4	4	4	4	3	3	3	1	5	5	4	56	Medium
19	1963	Repair and maintenance works are done in the north facade.	1	3	3	3	2	4	4	4	4	4	3	3	3	1	5	5	3	59	Medium
20	1969	More maintenance works is done in the north facade.	1	3	2	2	2	3	3	3	3	4	3	3	3	1	3	3	2	66	Medium
21	1981	The church burns again.	1	8	7	7	7	5	5	5	6	7	4	3	3	1	7	7	7	**19**	**Bad**
22	1994	The building reconstruction is finished.	1	2	2	2	2	2	2	2	3	4	3	3	3	1	2	2	2	72	Medium
23	2016	Current state of conservation	1	2	2	2	2	2	2	2	3	3	3	3	3	1	2	2	2	83	Good

6. Results and discussion

It seems then relevant to analyze the influence of the different possible anomalies and related causes on the functionality of built heritage. The historical reports consulted reveal that the roof of the churches is the most relevant element of construction (not only in the case study analyzed but in all the sample studied). The Institut Technique du Bâtiment et des Travaux Publics in France, after an analysis of 12,000 anomalies, concluded that roofs present more pathological problems than most building elements. A similar study carried out, more recently in Australia, also concluded that roofs are one of the elements most affected by pathological situations, and where a higher number of anomalies were observed (Ilozor, Okoroh, and Egbu 2004). The occurrence of anomalies in roofs usually leads to structural problems in the roof itself and in the rest of the building, and even damages the furniture and goods inside (Garcez et al. 2012a).

All the case studies analyzed (Seville parish churches) present anomalies in the main elements considered (Figure 6). Similarly, to what is described in the literature, in this study, the most of the anomalies detected occur in the roofs (32%), followed by anomalies in timber elements (25%), anomalies in the masonry (22%), anomalies in mortars and claddings (19%), and finally in the foundations (only 2%).

Concerning the pathology of the churches analyzed, one of the main problems is caused by the presence of moisture. In fact, the anomalies associated with humidity (AH) are the most common in the sample analyzed, occurring in 75% of the churches analyzed, during the period of time under analysis. The presence of moisture is usually associated with a defective roof (or problems in the roof system), which allow water to penetrate and cause damage to the structural elements of the buildings, their interior, and furniture, and also lead to a loss of quality in the indoor air (Olanrewaju, Faris, and Arazi 2010).

Moisture problems commonly happen in current buildings, with a higher impact on heritage buildings. In the sample analyzed, whenever infiltrations in the roof occur, a maintenance action is carried out, since this anomaly not only compromises the roofs' performance but also promotes the occurrence of various anomalies, namely peeling and blistering of the painted surfaces, stains, discolouration, mold growth, and corrosion, among others.

Another common situation is related with the presence of rising damp in the churches. Torres and de Freitas (2007) consider that moisture transfer in the walls of old buildings, which are in direct contact with the ground, leads to a migration of soluble salts responsible for most of the buildings' pathology.

Anomalies in the timber elements are also very common in the churches analyzed. Who (2009) refers that the growth of microorganism (such as fungi or bacteria) (Figure 7), are usually caused by prolonged presence of moisture on the building elements, associated with lack of ventilation, with adverse effects on the salubrity of the interior spaces.

In the sample analyzed, the anomalies most commonly detected are: accumulation of debris and superficial dirt (AA3); biological colonization (AH1); efflorescence/cryptoflorescence or carbonation (AH4); cracking/fractures (AM1); crumbling/disintegration/disaggregation (AM2); degradation of the mechanical characteristics (AM5); and warping, swelling, or other flatness deficiencies (AM7). These anomalies affect between 50% and 60% of all the case studies analyzed. Efflorescence is the most common defect detected in walls and claddings, essentially due to raising damp or capillarity phenomena. During the period of time analyzed in the historical records, detachment/loss of adherence (AH2) only occurs in 7% of the claddings in the churches analyzed, and the main causes of defects in the claddings are related with exterior mechanical actions and lack of maintenance. Cracking

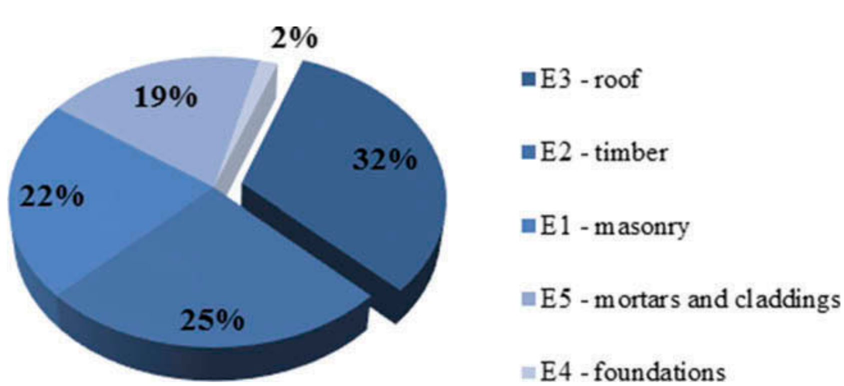

Figure 6. Frequency of the anomalies in the elements of historical buildings, based on the records of the 20 churches analyzed.

Figure 7. (a) A fungus infection of the timber roof could be due to permanent damp, dirt collection and natural causes; (b) external atmospheric actions (strong wind and rainwater); (c) active attack of xylophages' insects; and (d) Biological actions inside the roof.

and fractures are usually detected in roofs and timber elements, caused mainly by environmental actions and lack of maintenance.

The anomalies stains/colour change/discolouration (AA2), bulging (AM4) and broken or splintered elements/spalling/exfoliation (AM8) are less common, with a frequency of around 35%. Misalignment of cladding elements (AM10) only occurs in one case study. Collapse (AM13) of the tower bells occurred in around 6% of total of 390 historical records analyzed, mainly due to the occurrence of an earthquake. Some of the mechanical anomalies (AM) considered never occur in the sample analyzed: insufficient structural cross-sections (AM11); lack of downspouts and drain nozzles (AM14); absence of fastening elements (AM15). These anomalies are related with design and execution errors, which may reveal that the heritage buildings are less prone to this type of errors, being subjected to a more careful construction process, when compared with housing buildings.

Environmental actions (CC) and use and maintenance actions (CD) are the most common causes of anomalies in the churches analyzed. On the other hand, design and execution errors (CA) are less common, as well as exterior mechanical actions (CB).

As mentioned before, damp (CC2) and wind/rain action (CC3) are the most common causes of anomalies. Poor ventilation (CC5) is also one relevant cause of anomalies in churches located at the periphery of a city, which are usually open only once a week for the religious ceremonies.

Discrete phenomena also influence de degradation of the heritage buildings, even though they cannot be modelled the same as the other mechanisms. In the sample analyzed, 9.5% of the records reveal the occurrence of an earthquake or/and a fire. Also, in recent decades, in the city centre, vandalism actions have compromised the functionality of some buildings (detected in 2% of the historical data).

Use and maintenance actions (CD) have a tremendous impact on the churches' functionally. In general terms, careful application and frequent maintenance are equally important to guarantee a good performance of this type of buildings (Neto and de Brito 2012). In some situations, during the period of time analyzed, maintenance actions were carried out based on subjective criteria. 24% of the historical records reveal that a small intervention was performed, in general, repainting the church. In 9% of the cases, the maintenance of the church only contemplates the chapel, due to the problems in the roof or simply to programmatic issues or the availability of funds to perform conservation actions.

Part of the historical records, obtained from Vigil-Escalera Pacheco (1991), show that: in the parish churches used as case studies, restorations have been repeated, treating almost always the same elements and anomalies, namely the humidity on the naves' roofs and cracks in the vaults of the chapels, but the main problem is related with lack of maintenance of the roofs. This happens in the case study of the parish church of San Pablo (ID AZ-SPB), in which a maintenance action was performed in 2005 to solve infiltration problems; this action was inadequately performed, since it did not contemplate the analysis of the pathological situation of the building, being performed as a "standard" action, i.e., repairing the roof of the church. This case study was also repaired in 2007 and 2008, in order to restore the adequate functionality levels of the building. This lack of maintenance strategies leads to unnecessary costs, since it is impossible to adopt general methodologies, neglecting the analysis of the characteristics and the pathology of the buildings that will be subjected to the maintenance actions.

Therefore, it is fundamental to define accurate tools, which can be used by all stakeholders involved in the various stages and levels of activity, to establish integrated building maintenance routines (including periodic inspections, preventive works, and conservation and rehabilitation actions). Silva, de Brito, and Gaspar (2016) and Prieto et al. (2016b) proposed different tools for the physical and functional service life prediction of the buildings and their components, based on their pathological situation. These tools provide reliable information regarding the instant in which it is necessary to intervene, knowing the deterioration condition of the element under analysis, acting in accordance with its pathological situation. Successful maintenance plans can only be achieved through the analysis of the pathological situations of the heritage buildings under analysis, identifying the elements that require intervention, thus rationalizing resources and funds, avoiding repetitive placebo-like processes that do not solve the initial problem.

7. Conclusions

In this study, the serviceability and the pathological characterization of 20 heritage buildings located on Seville were analyzed. This analysis is based on historical data gathered from photographs, historical archives, and chronicles. Analyzing the functionality of these specific case studies, it is possible to establish the buildings performance over time in terms of functional degradation conditions, except for discrete events, which lead to unacceptable degradation levels. This knowledge can help in understanding the past functionality level of the buildings, identifying the most common pathological situations, thus predicting the future behavior of the buildings analyzed.

In 85% of the buildings under analysis, the time of refurbishment actions after a disastrous event was between 1 and 20 years. This result can be seen as a first approximation of the possible path in terms of intervention time in historical constructions 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 there are not available funds, the restoration occurs many years later, which also reveals the subjective criteria that affect the decision of intervening.

Using the buildings functionality over time and the historical refurbishment and maintenance actions recorded, it was possible to determine the most frequent anomalies and their causes. The roof is the one of the most vulnerable element, showing the higher incidence of anomalies and being responsible for the majority of the decisions to intervene. The occurrence of moisture is identified as the major cause of heritage buildings' pathology, and is a determinant environmental factor in the degradation process.

This approach allows understanding the weak points of this kind of buildings, which should be carefully analyzed during the periodic inspections. The analysis of the maintenance and conservation data may be able to demonstrate the success that can be achieved by identifying the optimum period of time to perform preventive maintenance actions, thus reducing the maintenance costs during the buildings life cycle, promoting the sustainability of the conservation policies. This study could be extended to other constructions and components, and can also be adjusted to different environmental context.

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