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Original article

Multiple linear regression and fuzzy logic models applied to the functional service life prediction of cultural heritage

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ABSTRACT

In this research, a proposal for the assessment of the functional service life of built heritage applying statistical tools is described. A fuzzy inference system is applied in order to establish a ranking in terms of functional service life for the built heritage, thus allowing prioritizing the maintenance and preventive conservation actions in homogeneous groups of buildings, and optimizing the costs involved in maintenance operations. The functionality of a sample of 100 parish churches was evaluated. However, the selection of maintenance strategies for buildings is usually a multiple criteria decision-making problem, encompassing various variables and constraints. Therefore, a multiple linear regression analysis is applied in order to rank the variables in terms of influence in the serviceability estimation of heritage buildings. Currently, social, environmental and economic reasons are raising concern about the durability and functional service life of heritage sites. The results obtained in this study are useful to researchers and stakeholders responsible for the maintenance of historical buildings, since they allow reducing their probability of failure. The preventive maintenance programs can be considered as a cost-effective and environmentally sustainable option to extend the serviceability of heritage buildings.

1. Introduction

Cultural heritage buildings are an important economic and cultural capital of European countries [1]. A monument is more than just the construction itself [2], being part of the local identity and a source of memory of historical events [3,4]. National governments and European institutions increasingly recognise the importance of the conservation of cultural assets [5]. In the last decades, there have been an important evolution in policies and practices regarding the preservation of heritage buildings. The Council of Europe proposed, in 2005, a new covenant for ratification concerning the cultural heritage [6]. The degree of involvement of nowadays societies is due to the consciousness of the need for a sustainable management of scarce resources [7].

Currently, around 50% of all building refurbishments in European cities are related in some way to heritage preservation [8]. The concept of conservation of cultural built heritage has evolved over the recent decades at the international level, in order to define multidisciplinary approaches to intervention in these buildings, thus leading to their maximum preservation [9,10]. In the conservation of built heritage, the building should be seen as a whole, thus protecting its constructive system and typological characteristics, maintaining its social function, responding to current lifestyles, avoiding its obsolescence and deterioration [11,12].

The conservation of these buildings is particularly complicated and is usually based on a more comprehensive analysis than just aesthetic or historical criteria. In fact, as referred by UNESCO [2], the conservation of built heritage requires the evaluation of several uncertain factors, demanding a thoughtful knowledge of history, a true understanding of the present and an ability to anticipate the future. The management of the conservation operations is usually a difficult task, conditioned by technical, financial and legislative issues [13]. Moreover, as mentioned by Alshweiky and Ünal [14], there is a lack of know-how, experts on conservation and funding for maintenance operations. Kim et al. [15] refer that the lack of accurate decision tools and the use of decision support systems for determining restoration priorities (usually, based only

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on the severity of damage) lead to ineffective tools for prioritizing execution needs and consequently to inefficient rehabilitation and maintenance operations.

2. Research aim

One way to improve the planning of the maintenance actions in heritage buildings, optimizing the resources applied in these interventions, is by understanding the degradation of their elements and identifying the instant beyond which they must be intervened [16]. Consequently, the preservation of architectural assets requires the development of methods, strategies and planning of maintenance operations [17]. Furthermore, it is necessary to analyse the heritage buildings context, proposing accurate strategies, establishing effective tools to aid the decision process for the definition of priorities for intervention [18]. Maintenance activities must be seen as an investment opportunity, adopting a series of measures to prevent both material and functional degradation. As mentioned by Vanier and Lacasse [19], the stakeholders must deal with difficult decisions concerning *when and how* perform maintenance and repair actions in the built environment. These difficulties are due to the lack of knowledge related to the service life prediction and the absence of methods to assist the asset manager in the definition of a proper maintenance, repair or replacement choices [20].

Currently, the service life prediction of the materials and components of the built heritage is an especially important issue to achieve their maximum longevity, avoiding the possible failure of the building and future extremely costly interventions [21]. Therefore, new methodologies are necessary in order to establish the instant in which it is necessary to intervene, thereby allowing a more rational definition of maintenance plans, adopting "just-in-time and fit-for-purpose" operations [22,23].

Therefore, in this study, statistical and fuzzy models are established to describe the functional service life of heritage buildings. Macías-Bernal et al. [24] initially proposed a fuzzy inference system (FIS) to model the functional service life of heritage, cultural and religious buildings. They identified 17 vulnerability and risks factors that affect the buildings' service life, establishing a mathematical model to determine the functionality index of the buildings analysed, which was called as Fuzzy Building Service Life (FBSL). This model was previous defined to solve a real problem, i.e. the Archdiocese of Seville intended to maintain and rehabilitate a set of religious buildings, and needed to know which buildings should be maintained and rehabilitated first and the sequence of intervention.

This methodology has been applied and improved by Prieto et al. [25] and Prieto et al. [26], intending to provide a priority ranking of maintenance actions based on the sample's performance. Prieto et al. [25] and Prieto et al. [26] applied the same inference rules, intending to validate the model by applying it to different sets of buildings with homogenous characteristics. This method, despite efficiently allowing the ranking of the maintenance needs of heritage buildings, is relatively complex, requiring the knowledge regarding the fuzzy inference system (which was established based on an expert survey) and the application of a specific software to obtain the functionality index of the case studies analysed.

Therefore, this study intends to improve the methodology previously proposed by the authors, establishing a new method simplifying the way in which the functionality of the buildings analysed is estimated. A multiple linear regression (MLR) analysis is used to describe a simplified model to predict the serviceability of the built heritage, identifying the variables that most contribute to the functional degradation phenomena of the religious buildings. For that purpose, a sample of 100 parish churches (with homogeneous constructive characteristics but different levels of serviceability) was examined. These models will support decision-makers in developing the most appropriate strategy for the future use of heritage buildings, considering the most relevant factors involved, and applying efficient maintenance strategies.

3. Functional service life model

3.1. Fuzzy set theory and model assumptions

The fuzzy set theory has been widely applied as a support tool for decision-making processes and in performance evaluation in engineering [27–29], and specifically in the decision-making support for the restoration and maintenance of historical buildings [30,31]. As mentioned by Kutut et al. [32], in the majority of the real-life situations, human judgements are vague and cannot be translated to numerical values, since human reasoning and decision-making are always associated with some degree of subjectivity. Fuzzy sets are able to deal with uncertain, imprecise and vague data, which is usually the information available for modelling real world phenomena [33–35]. Therefore, in this study, to deal with the uncertainty and vagueness associated with the evaluation of the functional condition of the churches analysed based on expert opinions, the fuzzy logic principles established by Zadeh [36] were used.

Unlike Boolean logic, in fuzzy logic, an element can belong to more than one set, with a given degree of membership [37]. Analysing for example the age of the building, classic logic only accepts extreme values, i.e. a building can only be "old" or "new"; on the contrary, in fuzzy logic, each proposition can be partially true and partially false, with a given degree of or membership to each of the conditions [38], i.e. a given building can be 30% "old" and 70% "new", belonging simultaneously to the two conditions.

A membership function μ allocates to each element a membership degree in the fuzzy set A, ranging from 0 to 1 [39]. The inputs variables are fuzzified in membership functions μ_A, U is universe of discourse, in which a fuzzy set can take any value in the range of [0,1], as described in equation (1).

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

In this fuzzy inference system (FIS), Gaussian-type membership functions are generally used in the input parameters, as they are considered the most appropriate, reaching a non-zero values at all points, except for the v_1 input variable, in which a trapezoidal membership function is applied. The system uses the fuzzy operator "and" as connector [26], i.e. "and" represents the intersection between two fuzzy sets. The intersection between fuzzy sets A and B is given by a fuzzy set $A\hat{B}$, which membership function as defined in Eq. (2) ([40], [26]):

$$\mu_{A \wedge B}(x,y) = T(\mu_A(x), \mu_B(y)) \tag{2}$$

$$T(x, y) = \min(x, y) \tag{3}$$

Where T(x, y) is a T-norm that complies with the commutative, associativity and monotony properties [41], as seen in Eq. (3).

The main stage of a fuzzy system is the base of knowledge, which contains a set of natural language rules and it consists of conditional statements. As mentioned by Vesely et al. [37], *there is one conditional statement R describing each known case, while individual fuzzy sets A, B, C, etc. within that statement R refer to the values of variables*, Eq. (4):

$$R = \text{If} \quad A \quad \text{and} \quad B \quad \text{then} \quad C \tag{4}$$

As an example, in the fuzzy inference system described in the manuscript, if "the drainage of water in the roof occurs rapidly" (A) and "the constructive system is adequate" (B) then "the durability of the roofing system is high" (C). The knowledge base, fuzzy rules and hierarchical structure are formed using a professional expert's survey (which is extensively described in Section 3.4). The fuzzy system applies the Mamdani inference system [42]. Fuzzy models can be considered as transparent models (Babuška 1998), describing the relationship between the input and output parameters by means of *if-then* rules. To illustrate the inference mechanism system applied, two examples of the inference rules established are presented in Eq. (5).

(5) IF $v1$-Geological location is VG-Very Good; AND $v3$-Environmental conditions is VG-Very Good; AND $v4$-Constructive system is a medium estimation; THEN the output (Vulnerability) is VG-Very Good.

IF $r6$-Load state modification is R-Regular; AND $r9$-Facilities is R Regular; AND Vulnerability is VB-Very Bad; THEN the output (Static-structural risks) is VB-Very Bad.

Finally, in the defuzzification step, crisp numerical predictions result from the fuzzy predictions using the "centre of gravity" algorithm [37]. Several alternative defuzzification methods are reviewed but centre of gravity is one of the most widely used, and is adopted in this study. The discrete case can be interpreted by a Riemann sum [26,43]. Eq. (6) presents the mathematical expression of the proposed model [24–26], allowing estimating the functional index — designated Fuzzy Building Service Life (FBSL) — of the heritage buildings. In other words, Eq. (6) presents the output of the model based on the inference rules and the fuzzy system proposed. As mentioned by Prieto et al. [26], the model presents a continuous property, i.e. the input membership functions are continuous, the universe of inference is continuous and the fuzzy sets are defined by continuous membership functions, instead of using membership values (discrete universe) [44,45], which implies that small changes in the inputs do not lead to a significant change in the output.

$$F_{BSL} = \frac{\Sigma_i y_i \bullet \mu_B(y_i)}{\Sigma_i \mu_B(y_i)} \tag{6}$$

The FBSL can be used to establish the probable loss or gain in functional service life of a building's elements for different lev els of maintenance. The computational application of the fuzzy model used in this study was implemented in fuzzy logic software developed at IMSE-CNM — Seville Institute of Microelectronics and National Microelectronics Centre and R&D&I centre belonging to CSIC — Spanish National Research Council [66]. It is named Xfuzzy3.0.

3.2. Variables included in the model

The deterioration, failure and potential collapse of historical buildings usually occur due to [46,47]:

- rain water runoff action associated with the performance and design of the roof structure;
- soil settlement and relative movement of the foundation;
- inadequacy of the load-carrying structural system;
- lack of strength of the materials applied;
- design problems;
- local and environmental effects associated with the geographic location of the building.

Various authors [48–50] refer that the cultural heritage is usually subjected to:

- static-structural hazards, such as floods, geotechnical problems, seismic actions, among others;
- environmental hazards, such as the weather conditions, pollution, among others;
- and anthropogenic factors, such as fires, population and tourism.

Furthermore, it is important to analyse the combined effect of the probability of occurrence of a threatening event (hazards) and its potential consequences (loss of life or injury, property deterioration, social and economic obsolescence), which is directly related with existing vulnerabilities (e.g. physical or environmental vulnerabilities) [51,52].

Therefore, this study intends to contemplate all the relevant variables, including risks and vulnerabilities, for the description of the loss of functionality of heritage buildings. The proposed model was defined based on the specifications established in the international standard ISO 31000: 2009 [69], which establishes the basic concepts to manage and assess the risks of the buildings analysed, contemplating the nature and type of the consequences, estimating the probability of future occurrence, and therefore allowing establishing the necessity of intervene in each building considered, as well the priority of intervention in a set of heritage buildings based on the estimated functional service life of each case study analysed [25]. Consequently, 17 input parameters were included in the fuzzy model [24,26]:

- vulnerabilities: v_1: geological location; v_2: roof design; v_3: built context; v_4: constructive system; v_5: preservation; "vulnerabilities" include the variables related with the characteristics of the building, i.e. that portray the physical reality of the building at the inspection time, which usually remains unchanged over time;
- static-structural risks: r_6: load state modification; r_7: live loads; r_8: ventilation; r_9: facilities; r_{10}: fire; r_{11}: inner environment; static-structural risks include all the variables that are related with the safety of the building (structural, in case of fire, in use) and the factors that vary in intensity and magnitude throughout the life cycle of buildings, depending on each specific circumstance;
- atmospheric risks: r_{12}: rainfall; r_{13}: temperature. The rainfall conditions were evaluated based on the data of the Municipality board for Environmental issues of Andalusia, establishing four levels of risk according to the intensity of rainfall in the different areas of Seville's province. The variable "temperature" was defined comparing the maximum and minimum average annual temperatures in each municipality of Seville, assuming that the most unfavourable situation corresponds to buildings located in an area with more days per year with the highest temperature variation. The environmental conditions were established in relation with the more extreme conditions of the Seville Archdiocese, in order to compare the most unfavourable situations with the real conditions that affect each specific building considered;
- anthropic risks: r_{14}: population growth; r_{15}: heritage value; r_{16}: furniture value; r_{17}: occupancy.

Table 1 presents the numerical translation of the variables considered, explaining the different possibilities for each variable. The evaluation of the variables analysed shown in Table 1 contemplates three options, the most favourable, the current situation (represented by the middle point) and the most unfavourable situation. However, intermediate situations can also be evaluated by the model; for that, an in-between value should be adopted.

3.3. Characterization of the sample

This study is based on 100 heritage buildings located in the province of Seville, Andalusia region, Spain (Fig. 1), corresponding to an area of 14,000 km^2. The geographical territory ranges from the southeast, Atlantic Ocean to the northwest close to Sierra Norte Natural Park, which is categorised as a warm Mediterranean weather with an annual average temperature of 18.5 °C; winters are usually mild while summers are remarkably hot. The majority of the historic buildings analysed were built between the 14th and 16th centuries, including some constructions built in the 17th–18th centuries, in a Baroque style. Consequently, the parish

Table 1
Descriptive variables valuation of the model.

Variables	Variables designation	Qualitative valuation	Quantitative valuation	Descriptive valuation
v_1	Geological location	Good	1.0	Optimum ground conditions (very stable soil – rock bottom)
		Average	2.5	Ground conditions within acceptable limits of stability
		Bad	4.0	Very unfavourable ground conditions (clay soil)
v_2	Roof design	Good	1.0	Easy and fast evacuation of water on deck (ideal situation – semi-spherical dome)
		Average	4.5	Good conditions in terms of evacuation of rainfall
		Bad	8.0	Complex and slow evacuation of water
v_3	Environmental conditions	Good	1.0	Building without constructions around it
		Average	4.5	Building between constructions
		Bad	8.0	Building between complex constructions
v_4	Constructive system	Good	1.0	Uniform characteristics of constructive system
		Average	4.5	Heterogeneous characteristics of constructive system
		Bad	8.0	Intermingled different constructive system
v_5	Preservation	Good	1.0	Optimal state of conservation
		Average	4.5	Normal state of conservation
		Bad	8.0	Building in a neglected state of conservation
r_6	Load state modification	Good	1.0	Without any apparently modification
		Average	4.5	Symmetric and balanced modifications
		Bad	8.0	Disorderly modifications without any pattern
r_7	Live loads	Good	1.0	Live loads below the original level
		Average	4.5	Live loads equal to the original level
		Bad	8.0	Live loads higher than the original level (warehouse)
r_8	Ventilation	Good	1.0	Natural cross-ventilation in all or in several areas
		Average	4.5	Natural cross-ventilation in some areas
		Bad	8.0	No natural cross-ventilation
r_9	Facilities	Good	1.0	All facilities are in use and under standards conditions
		Average	4.5	Some facilities are in use
		Bad	8.0	Facilities are not ready to be used
r_{10}	Fire	Good	1.0	Incombustible structure and low fire load
		Average	4.5	Combustible structure and medium fire load
		Bad	8.0	Combustible structure and high fire load
r_{11}	Inner environment	Good	1.0	Low level of health, cleanliness and hygiene of the building's spaces
		Average	4.5	Medium level of health, cleanliness and hygiene of the building's spaces
		Bad	8.0	Maximum level of health, cleanliness and hygiene of the building's spaces
r_{12}	Rainfall	Good	1.0	Area with low annual rainfall
		Average	4.5	Area with medium annual rainfall
		Bad	8.0	Area with maximum annual rainfall
r_{13}	Temperature	Good	1.0	Area with low temperature differences
		Average	4.5	Area with medium temperature differences
		Bad	8.0	Area with maximum temperature differences
r_{14}	Population growth	Good	1.0	Population growth greater than 15%
		Average	4.5	Population growth 0%
		Bad	8.0	Population growth less than 5%
r_{15}	Heritage value	Good	1.0	Properties with great historical value
		Average	4.5	Properties with average historical value
		Bad	8.0	Properties with low historical value
r_{16}	Furniture value	Good	1.0	Social, cultural and liturgical appreciation (high value)
		Average	4.5	Social, cultural and liturgical appreciation (average value)
		Bad	8.0	Social, cultural and liturgical appreciation (low value)
r_{17}	Occupancy	Good	1.0	High activity in the building (high occupancy)
		Average	4.5	Media activity in the building (average occupancy)
		Bad	8.0	Low activity in the building (low occupancy)

churches have homogeneous constructive, cultural, political and regulatory features. However, the chronology and stylistic characteristics of Mudejar-Gothic buildings in the region have features that are unique to this kind of construction [50]. The Mudejar-Gothic churches in the province of Seville are morphologically characterized by this stylistic dualism: a vaulted Gothic apse and a body of three naves with a timber roof of Moorish origin [53]. As described by Zamarreño et al. [53], *its brick walls are complemented with quadrangular, and in some cases, octagonal pillars with raised brick mouldings as decoration*.

3.4. Condition survey

The condition survey is quantified and validated by a group of 15 professionals with expertise in the management of built heritage [24]. The expert survey is performed in the model's design stage. The expert profiles are related with the areas of rehabilitation and pathology on construction; direction of accredited laboratories of building materials; restoration; architecture; archaeology; fireman commanders; heads of building maintenance of a municipality provincial capital of 700,000 inhabitants; the direction of a World Heritage conservation building; conservation of a Port Authority; management of an insurance company at international level; and experts in quality management in buildings [26]. The 17 input variables considered were identified based on the analysis of the different factors that influence the functionality and service life of religious buildings, after review the following documents: Spanish Technical Building Code; National Cathedral Plan; Law on Construction Planning; Heritage Conservation Network; UNE 41805:2009 IN [71]; ISO 15686 [68]. Additionally, a Delphi methodology (applied in two rounds), through the *Opina* software property of University of Seville [70], was used to obtain all the expert's survey. In the expert survey, two questions are asked related with the 17 factors proposed. The first one intends to understand whether the expert agrees that the factors considered were relevant in determining the service life of the building. The second question intends to

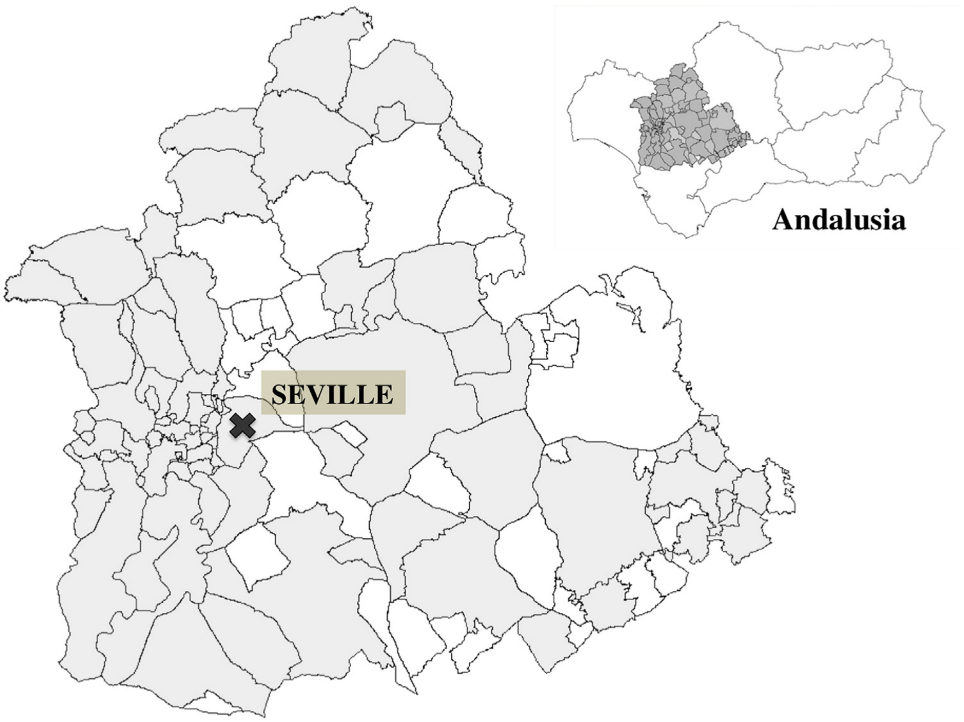


Fig. 1. Map of the study's scope by municipalities, Province of Seville, Andalusia, Spain.

understand the relevance of each factor in the overall functionality and durability of the building, adopting a numerical scale ranging between 1 (low influence) and 10 (high influence). Table 2 presents the 17 input factors ranked by the degree of relevance that the experts have assigned to each one of the factors, indicating the average value obtained in a scale of one to ten.

Table 2
17 input parameters ranked by the degree of relevance that the experts assigned to each of the factors (data sourced from [24]).

Input variable	Description	Factor incidence level in functional durability. Average value[a]	Factor incidence level in functional durability. Standard deviation
v_5	Preservation	8.64	2.157
r_{10}	Fire	8.29	1.567
r_6	Load state modification	8	1.748
v_2	Roof design	8	1.804
r_9	Facilities	7.43	1.804
r_{15}	Heritage value	7.11	1.748
r_{17}	Occupancy	7.09	1.567
v_1	Geological location	6.92	1.286
v_4	Constructive system	6.83	1.567
r_{12}	Rainfall	6.62	1.489
r_7	Overloads	6.54	1.859
r_{14}	Population growth	6.38	1.690
r_{13}	Temperature	6.38	1.433
r_8	Ventilation	6.29	1.502
v_3	Built context	6.27	1.567
r_{16}	Furniture value	6.25	2.063
r_{11}	Inner environment	5.86	1.120

[a] The influence of each variable is quantified adopting a numerical scale ranging between 1, low influence, and 10, high influence.

4. Application of multiple linear regression to identify the relevant parameters in the serviceability of historical buildings

Regression analysis is one of the methods most commonly used to measure the relationship between two or more variables [54], thus predicting the behaviour of a dependent or endogenous variable, according to one or more independent or explanatory variables. Multiple linear regression is frequently used as an empirical model or approximating function, which allows establishing a mathematical model to describe a given real-world phenomenon [55]. Generally, the relationship between the dependent and the independent variables is given as presented in Eq. (7) [56].

$$y_i = \beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \cdots + \beta_p x_{pi} + \varepsilon_i \tag{7}$$

Where y_i is the dependent variable; β_0, β_{1i}, β_{2i}, ..., β_{pi} the regression coefficients, x_{1i}, x_{2i}, ..., x_{pi}, the independent variables and ε_i the random errors of the model. The linear regression coefficients (B) are obtained by the method of least squares.

Recently, various studies [38,56,57] address the application of this statistical technique for the service life prediction of claddings and as a tool to maintenance decision support. As mentioned in the previous section, in this study, the serviceability of the historical monuments analysed is obtained based on an expert survey. This model, which applies a fuzzy logic inference system, leading to a functionality index (FBSL), is very complex and time-consuming, requiring specific software for its practical application. Furthermore, the model encompasses all the relevant variables, considering 17 input parameters. Therefore, in this study, the multiple linear regression (MLR) analysis is applied to model the functionality of built heritage, proposing a new model, functioning as a simplification of the FBSL model, thus reducing the complexity of the model and the number of variables included in the model.

Therefore, the first stage of the definition of the MLR model is the identification of the variables that most contribute to the explanation of the dependent variable, i.e. the functionality of the cultural heritage buildings. As mentioned by Martin et al.

Table 3
Summary of the multiple linear regression model obtained for the prediction of the FBSL index, with 11 variables.

Model	R	R^2	R^2_{adjusted}	Square of the mean square error
1	0.703[a]	0.495	0.489	9.839
2	0.852[b]	0.725	0.719	7.293
3	0.898[c]	0.807	0.801	6.145
4	0.920[d]	0.846	0.839	5.517
5	0.937[e]	0.878	0.872	4.928
6	0.947[f]	0.898	0.891	4.546
7	0.954[g]	0.911	0.904	4.267
8	0.960[h]	0.923	0.916	3.997
9	0.965[i]	0.931	0.924	3.803
10	0.969[j]	0.938	0.931	3.604
11	0.970[k]	0.942	0.934	3.525

[a] Predictors: (Constant), v_2.
[b] Predictors: (Constant), v_2, r_{17}.
[c] Predictors: (Constant), v_2, r_{17}, r_7.
[d] Predictors: (Constant), v_2, r_{17}, r_7, v_3.
[e] Predictors: (Constant), v_2, r_{17}, r_7, v_3, r_{14}.
[f] Predictors: (Constant), v_2, r_{17}, r_7, v_3, r_{14}, v_5.
[g] Predictors: (Constant), v_2, r_{17}, r_7, v_3, r_{14}, v_5, r_{10}.
[h] Predictors: (Constant), v_2, r_{17}, r_7, v_3, r_{14}, v_5, r_{10}, v_1.
[i] Predictors: (Constant), v_2, r_{17}, r_7, v_3, r_{14}, v_5, r_{10}, v_1, r_{12}.
[j] Predictors: (Constant), v_2, r_{17}, r_7, v_3, r_{14}, v_5, r_{10}, v_1, r_{12}, r_{15}.
[k] Predictors: (Constant), v_2, r_{17}, r_7, v_3, r_{14}, v_5, r_{10}, v_1, r_{12}, r_{15}, v_4.

[58], an efficient service life prediction method should be able to define the relevant variables. In this study, a stepwise technique is applied intending to identify which variables are most significant. In this method, only the statistically significant independent variables are included in the model, analysing all the hypotheses of the regression, thus eliminating the effects of multicollinearity, i.e. pseudo-independent variables that are interrelated, thus jeopardizing the multiple regression analysis [59]. In the stepwise technique, the independent variables were introduced in the model from the most significant variable, with high impact in the correlation coefficient of the model, to the less significant variable [59]. For the definition of the MLR models, the SPSS (Statistical Package for Social Sciences) software was used.

In the definition of the MLR model, the functionality index is considered the dependent variable, analysing the 17 input variables from the fuzzy inference system (FIS) model. Eq. (8) presents the MLR model obtained, allowing predicting the functionality of the heritage buildings according to the 11 explanatory variables considered.

$$\begin{aligned}\text{FBSL} = &-1.902v_1 - 3.396v_2 - 0.629v_3 - 1.160v_4 - 3.373v_5\\ &- 2.173r_7 - 2.297r_{10} - 1.318r_{12} - 1.286r_{14}r14\\ &- 1.531r_{15} - 1.077r_{17} + 115.257\end{aligned} \quad (8)$$

Where v_1 is geological location, v_2 roof design, v_3 environmental conditions, v_4 constructive system, v_5 conservation state (preservation condition), r_7 live loads, r_{10} risk of fire, r_{12} exposure to rainfall, r_{14} population growth, r_{15} heritage value and r_{17} conditions of occupancy. To apply this model, the explanatory variables must be replaced by their numerical value, shown in Table 1.

Table 3 presents the summary of the multiple linear regression model obtained for the prediction of the FBSL index. This model presents correlation and determination coefficients of 0.960 and 0.923, respectively; thus revealing a very strong correlation between the FBSL obtained by the expert survey and the FBSL values predicted by the MLR model. The determination coefficient obtained reveals that 92.3% of the variability of the FBSL index can be explained by the 11 variables included in the model, while the remaining 7.7% is due to other causes that were not analysed in this study.

In Table 4, the ANOVA table of the model obtained for the prediction of the FBSL index is presented. The *F* test is usually used to determine the explanation capacity of the proposed model [56]. For a 5% level of significance, 11 numerator degrees of freedom and 88 denominator degrees of freedom, a critical value of *F* of 1.900 was obtained, significantly lower than the value obtained in the ANOVA analysis (129.330), which reveals that the model has a statistically significant explanation capacity, and there is at least one statistically significant independent variable.

Table 5 shows the regression coefficients used in the mathematical equation (8), which expresses the functionality of the built heritage according to the independent variables considered. The *t*-test allows evaluating whether each variable is useful to predict/explain the dependent variable. In this study, for a level of significance of 5% and for a sample of 100 case studies, the critical value of *t* is 1.660, significantly lower (in absolute value) than the *t* values obtained for the eleven independent variables included in the model. Also, the significance values present in Table 5 are

Table 4
ANOVA table of the model obtained for the prediction of the FBSL index, with 11 variables.

Model[a]	Variation – Sum of the squared deviations	Freedom degree (FD)	Mean squared deviation	*F*	Significance
11					
Regression	17677.911	11	1607.083	129.330	0.000[b]
Residual	1093.509	88	12.426		
Total	18771.420	99			

[a] Predictors: (Constant), v_2, r_{17}, r_7, v_3, r_{14}, v_5, r_{10}, v_1, r_{12}, r_{15}, v_4.
[b] Dependent variable: FBSL index.

Table 5
Regression coefficients of the model obtained for the prediction of the FBSL index, with 11 variables.

Model[a]	Linear regression coefficients		Standardized coefficients	t	Significance
	β	Standard deviation associated to the regression coefficients	Beta		
11					
(Constant)	115.257	2.335		49.359	0.000
v_2	−3.396	0.359	−0.378	−9.463	0.000
r_{17}	−1.077	0.386	−0.110	−2.793	0.006
r_7	−2.173	0.680	−0.117	−3.198	0.002
v_3	−0.629	0.327	−0.076	−1.921	0.058
r_{14}	−1.286	0.315	−0.144	−4.083	0.000
v_5	−3.373	0.645	−0.179	−5.226	0.000
r_{10}	−2.297	0.406	−0.197	−5.653	0.000
v_1	−1.902	0.677	−0.101	−2.811	0.006
r_{12}	−1.318	0.333	−0.147	−3.955	0.000
r_{15}	−1.531	0.424	−0.117	−3.611	0.001
v_4	−1.160	0.517	−0.087	−2.243	0.027

[a] Dependent variable: FBSL index.

always lower than 5%, thus revealing that all the variables are statistically relevant, and the model presents a good adjustment to the reality that it intends to model.

The proposed model presents a strong correlation between the FBSL predicted and the values obtained by the fuzzy inference system (FIS) model (based on the real condition of the churches inspected, according to the expert survey performed). However, the proposed model is still relatively complex, with a large number of predictors. Therefore, a simplified model is proposed, easier to apply in practice, with only six variables. The simplified or reduced model was established ensuring that the new model is able to portray adequately the functionality index of the churches under analysis and does not imply a reduction in the accuracy of the overall MLR model higher than 5%. The main drawback of the simplified model is that, as usually occurs in mathematical modelling, the simplification of the model leads to a slight reduction of their accuracy. This model corresponds to model 6 in Table 3, with a determination coefficient of 0.898. When compared with the global model, the simplified model only presents a decrease of its statistical significance of 4.4%, which is a residual value given the much higher simplicity obtained.

The simplified model shows a very strong correlation between the predicted and the observed functionality index, revealing that 89.9% of the variability of the functionality of the churches analysed can be explained by the six variables included in the model. Eq. (9) presents the numerical equation of the relationship between the FBSL index and the explanatory variables.

$$\text{FBSL} = -3.954v_2 - 2.247v_3 - 3.076v_5 - 3.241r_7 - 1.876r_{14} - 2.675r_{17} + 109.320 \qquad (9)$$

Where v_2 is roof design, v_3 environmental conditions, v_5 conservation state (preservation condition), r_7 live loads, r_{14} population growth and r_{17} conditions of occupancy. For the application of the simplified model, the explanatory variables must be replaced by their numerical value, presented in Table 1.

Table 6 shows the ANOVA table of the simplified model. For this model, it is also concluded that the model has a statistically significant capacity, since the value of F (135.913) is much higher than the critical value (equal to 2.183, obtained by the Fisher–Snedecor tables, adopting a 5% significance level, six numerator degrees of freedom and 93 denominator degrees of freedom).

Table 7 presents the regression coefficients. All the variables included in the simplified model are statistically relevant, presenting an absolute t value of the regression higher than the critical value of t (equal to 1.660, obtained by the *t-Student* distribution tables, for a significance level of 5% and for a sample of 100 case studies). The analysis of the statistical parameters analysed, reveal that the model is well adjusted to the dataset, and is able to describe the variability of the serviceability of the cultural buildings analysed.

5. Discussion of the results

The method presented in this study allows evaluating the functionality of the churches analysed. This methodology considers the consequences of environmental, static-structural and anthropogenic conditions on the functional service life of cultural heritage (given by the serviceability index — FBSL). The application of the FBSL model implies the knowledge regarding the fuzzy logic inference system adopted, as well the use of the computational application or the fuzzy model software developed. This model is more complex but also more accurate, encompassing all the relevant variables. Therefore, the models proposed by the MLR allow simplifying the fuzzy model, estimating the functionality level and the ranking of the maintenance needs of the buildings analysed, applying a simple equation, easily applied by the different stakeholders (managers, designers, architects, building pathologists, engineers, among others), not requiring expert knowledge regarding fuzzy inference systems or complex software. Necessarily, the gain in simplicity leads to a loss in the accuracy of the model, even though, as mentioned by different authors [60,61], the decisions to be made

Table 6
ANOVA table of the model obtained for the prediction of the FBSL index, with six variables.

Model[a]	Variation – Sum of the squared deviations	Freedom degree (FD)	Mean squared deviation	F	Significance
6					
Regression	16849.806	6	2808.301	135.913	0.000[b]
Residual	1921.614	93	20.663		
Total	18771.420	99			

[a] Predictors: (Constant), v_2, r_{17}, r_7, v_3, r_{14}, v_5.

[b] Dependent variable: FBSL index.

Table 7
Regression coefficients of the model obtained for the prediction of the FBSL index, with six variables.

Model[a]	Linear regression coefficients		Standardized coefficients	t	Significance
	β	Standard deviation associated to the regression coefficients	Beta		
11					
(Constant)	109.320	2.678		40.820	0.000
v_2	−3.954	0.403	−0.440	−9.802	0.000
r_{17}	−2.675	0.375	−0.274	−7.132	0.000
r_7	−3.241	0.778	−0.175	−4.167	0.000
v_3	−2.247	0.328	−0.271	−6.855	0.000
r_{14}	−1.876	0.372	−0.210	−5.043	0.000
v_5	−3.076	0.736	−0.163	−4.181	0.000

[a] Dependent variable: FBSL index.

on maintenance actions affecting the built heritage should be aided by user-friendly tools that can be easily applied by the stakeholders.

Concerning the ranking of the maintenance and restoration activities, Prieto et al. [26] proposed a numerical scale to correlate the FBSL index and the time until the next maintenance action. Adopting these criteria, a church with a FBSL index under 34 requires an immediate intervention; in the sample analysed, 23 churches require an immediate intervention according to the fuzzy logic model, and the MLR model with 11 variables identify correctly 91% (21 of the case studies) that actually require immediate intervention. The simplified model with only six variables, besides being simpler, loses some accuracy, only identifying correctly 74% of the case studies that require immediate intervention. On the other side of the hierarchical scale, there are 20 churches in a very good conservation state that do not require interventions in the next 50 years. Both MLR models identify correctly 90% of these case studies. Therefore, although the MLR models are not perfect, the results reveal that both models present high levels of accuracy and an adequate behaviour in the description of a complex phenomenon such is the functionality condition of heritage buildings.

The MLR models reveal that, as expected, there is an inverse proportional relationship between the functionality of the churches and their vulnerability and risks, i.e. buildings subjected to higher risks and with higher vulnerability conditions, present lower functionality indexes. To illustrate this conclusion, Fig. 2 presents the correlation between the intrinsic vulnerability of the buildings and the external risks, and the influence of these parameters in the functional performance of the buildings. Fig. 2 presents a theoretical analysis, similar to a sensitivity analysis, evaluating in which way the FBSL index varies when the risks and vulnerabilities of the building also vary. Therefore, a theoretical functionality index was defined, given by the following equation: Theoretical FBSL = 1/(V – (V*R)) [24]. In this analysis, the “x” axis shows the risks of the building considered as a whole, the “y” axis presents the theoretical functionality of the building and different categories of vulnerability are analysed. The vulnerability of the building is also analysed as a whole, i.e. when the five variables considered as “vulnerability variables” are quantified by 1 means that the building presents an extremely low vulnerability level (e.g. the building presents optimum ground conditions ($v1$ — geological location), the drainage system of the roof is extremely efficient ($v2$ — roof design), the building is in an area without constructions around it ($v3$ — environmental conditions), it presents uniform characteristics of the constructive system ($v4$ — constructive system) and is in an optimal conservation state ($v5$ — preservation)). On the opposite, when the vulnerability of the building is extremely high, the vulnerability value is equal to 8. The evaluation of these variables was discussed in Table 1. In this theoretical analysis, the theoretical vulnerability varies between 1 (extremely low vulnerability level) to 8 (extremely vulnerable) and the same occurs to the theoretical risks, in which 1 means a building subjected to very low risks and 8 a building extremely exposed to risks.

The analysis of Fig. 2 reveals that when the risks are low, the building’s functionality depends on its vulnerability, presenting a wide range of FBSL values for different vulnerability values. As mentioned by Rashed and Weeks [62], the concept of vulnerability differs from that of risk, since it is not dependent from any certain magnitude of a given event, but dependent on the context in which that event occurs. In fact, the results show that, as the values of the risks increase, the building’s vulnerability is no longer so relevant, since against very serious hazards, such as an earthquake, there are no 100% safe buildings, and the functionality of the building decreases significantly, regardless of their degree of vulnerability.

The multiple linear regression models proposed allow identifying the more relevant variables for the description of the functionality of the churches analysed. Fig. 3 presents the weight of the different variables for the explanation of the variability of the serviceability of the buildings analysed. On the left, the relative weight of the 11 variables considered in the overall MLR model is analysed and, on the right, the six variables included in the simplified MLR model are analysed. Fig. 3 presents for both models the relative importance of each variable to the estimation or for the description of the variability of the functionality index of the heritage buildings analysed. For the multiple linear regression models proposed, the roofs’ design is the most relevant variable, which explain by itself more than 50% (exactly 52% for the model with 11 variables and 55% for the model with six variables) of the variability of the functionality level of the churches, since in several cases, the decision to intervene is exclusively based on the roof’s degradation condition. In the proposed models, occupancy is also a very relevant parameter, followed by live loads, environmental conditions, population growth and preservation condition. Macías-Bernal et al. [24] have discussed the weighing of the 17 input parameters according to the expert opinion, concluding that the preservation condition, risk of fire, load state modification and roof’s characteristics are the most relevant factors (Table 2). In this study, the sequence or the order of relevance of each variable is different from the study of Macías-Bernal et al. [24]. Naturally, different models lead to different conclusions, and the evaluation of the relative importance of each variable is subjective, since there are different possible outcomes to the question asked during the expert survey “which is the most relevant factor for the loss of functionality of cultural heritage”. Moreover, these models are based on the real evaluation of the 100 churches inspected by experts, which always involve complex reasoning perceptions and subjective evaluations of the observed reality.

For clarity’s sake, a case study is analysed, in order to discuss the relevance of the various variables evaluated in this study. Fig. 4 presents the Los Sagrados Corazones church, located in San Juan de Aznalfarache, and several pictures, related with the different factors involved in the serviceability of the built heritage, are shown.

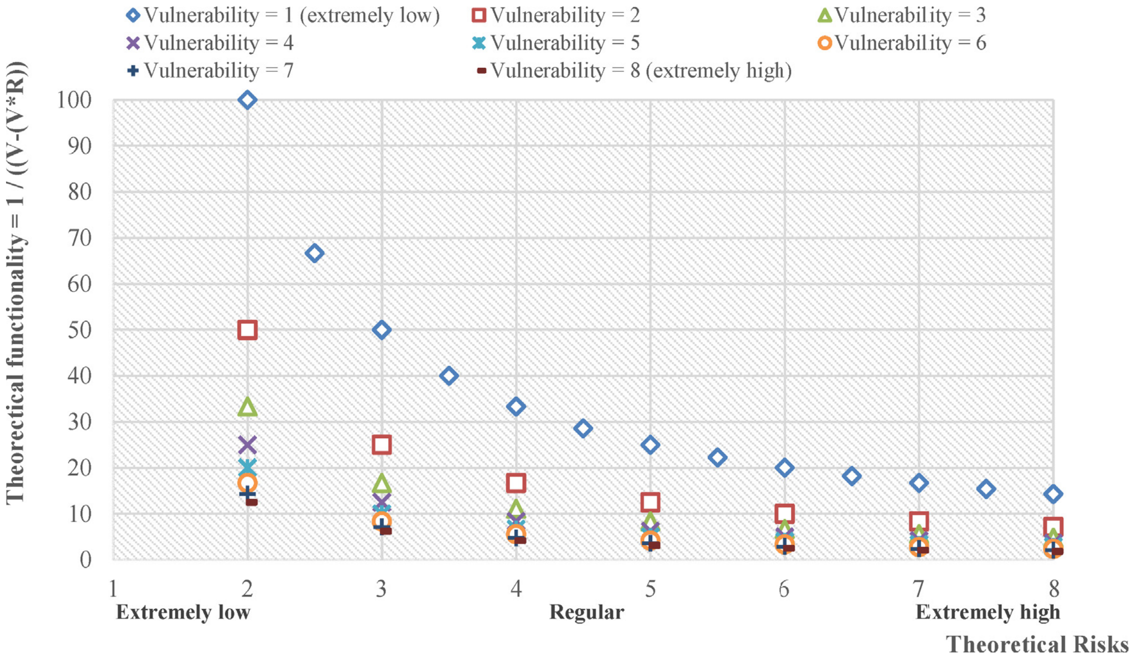


Fig. 2. Relationship between functionality and risks.

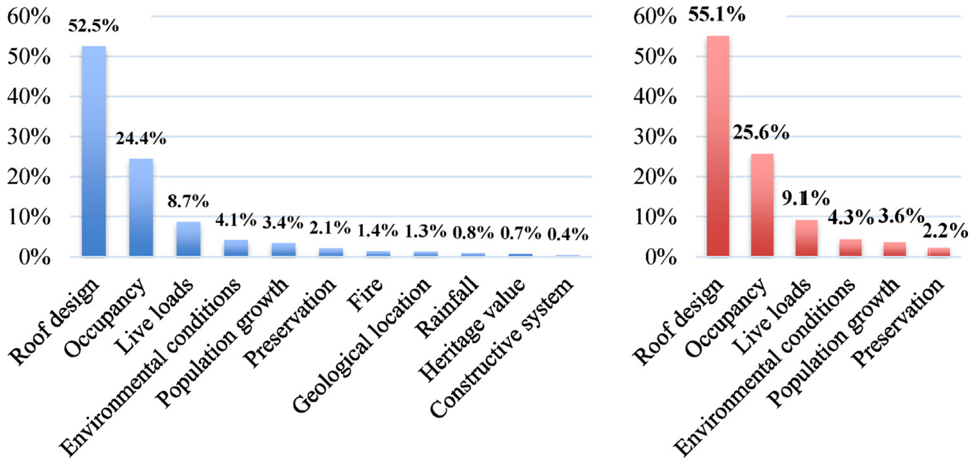


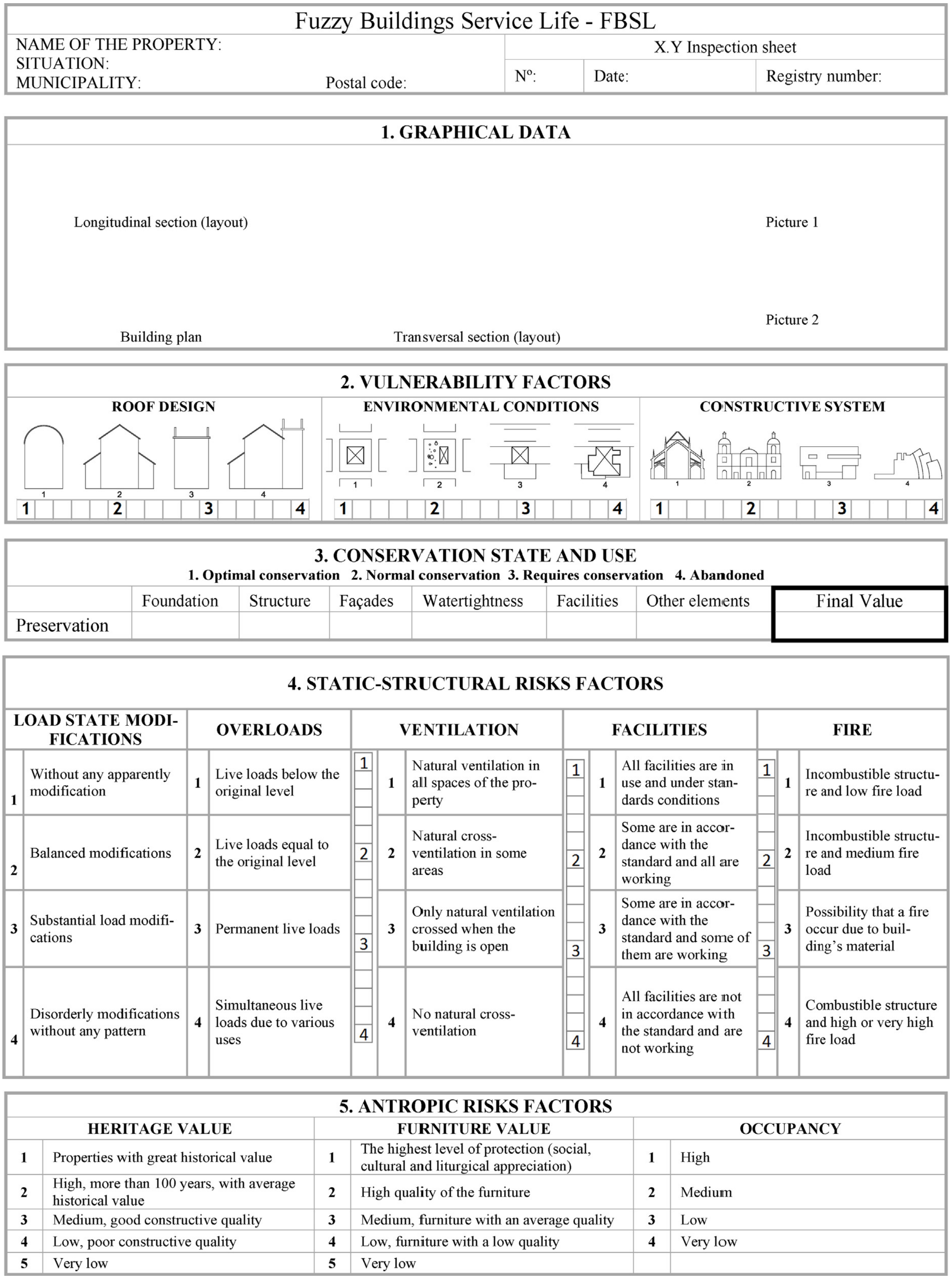
Fig. 3. Relative weight of the variables included in the global model (left) and in the simplified model (right).

Table 8
Practical application to one heritage building analysed.

Variables involved in the definition of the functional service life	Valuation	Parish Church	Municipality	Functionality	Functionality obtained by the MLR model
Vulnerability					
v_1	3	Los Sagrados Corazones	San Juan de Aznalfarache	37.981	44.695
v_2	2				
v_3	6				
v_4	4				
v_5	2				
Risks					
r_6	4				
r_7	4				
r_8	4				
r_9	4				
r_{10}	6				
r_{11}	3				
r_{12}	4				
r_{13}	3.5				
r_{14}	2				
r_{15}	4				
r_{16}	4				
r_{17}	6				

Fig. 4. Parish church Los Sagrados Corazones (San Juan de Aznalfarache).

Table 8 presents the quantification of the variables analysed, for this case study. The evaluation presented in Table 8, related with the case study under analysis, corresponds to the assessment made by an expert, during the visual inspection *in situ*, which evaluates the 17 variables using a more extensive file with the detailed explanation of each variable and an inspection sheet (Fig. 5) for the registration of the observed condition of the building. The roof's design is an extremely relevant parameter, since the inadequate drainage of water in the roof compromises the whole building conditions, promoting its deterioration. The roof's design (v_2) is directly related with the conservation condition, and historical data related with the preservation operations performed in the building reveals that, over time, the buildings have commonly suffered not only design changes, but also essential geometrical variations (e.g. increases of the roof's slope, reducing the vulnerability of the roof to wind and rainfall risks (r_{12})). During the expert survey performed to define the fuzzy inference system model (FBSL model), some explanations was obtained from the professional experts consulted:



Fuzzy Buildings Service Life - FBSL

NAME OF THE PROPERTY: SITUATION: MUNICIPALITY: Postal code:	X.Y Inspection sheet Nº: Date: Registry number:

1. GRAPHICAL DATA

Longitudinal section (layout)

Picture 1

Picture 2

Building plan

Transversal section (layout)

2. VULNERABILITY FACTORS

ROOF DESIGN	ENVIRONMENTAL CONDITIONS	CONSTRUCTIVE SYSTEM
1 2 3 4	1 2 3 4	1 2 3 4
1 2 3 4	1 2 3 4	1 2 3 4

3. CONSERVATION STATE AND USE

1. Optimal conservation 2. Normal conservation 3. Requires conservation 4. Abandoned

	Foundation	Structure	Façades	Watertightness	Facilities	Other elements	Final Value
Preservation							

4. STATIC-STRUCTURAL RISKS FACTORS

LOAD STATE MODIFICATIONS		OVERLOADS		VENTILATION		FACILITIES		FIRE	
1	Without any apparently modification	1	Live loads below the original level	1	Natural ventilation in all spaces of the property	1	All facilities are in use and under standards conditions	1	Incombustible structure and low fire load
2	Balanced modifications	2	Live loads equal to the original level	2	Natural cross-ventilation in some areas	2	Some are in accordance with the standard and all are working	2	Incombustible structure and medium fire load
3	Substantial load modifications	3	Permanent live loads	3	Only natural ventilation crossed when the building is open	3	Some are in accordance with the standard and some of them are working	3	Possibility that a fire occur due to building's material
4	Disorderly modifications without any pattern	4	Simultaneous live loads due to various uses	4	No natural cross-ventilation	4	All facilities are not in accordance with the standard and are not working	4	Combustible structure and high or very high fire load

5. ANTROPIC RISKS FACTORS

HERITAGE VALUE		FURNITURE VALUE		OCCUPANCY	
1	Properties with great historical value	1	The highest level of protection (social, cultural and liturgical appreciation)	1	High
2	High, more than 100 years, with average historical value	2	High quality of the furniture	2	Medium
3	Medium, good constructive quality	3	Medium, furniture with an average quality	3	Low
4	Low, poor constructive quality	4	Low, furniture with a low quality	4	Very low
5	Very low	5	Very low		

Fig. 5. Inspection sheet used by the expert during the visual inspection in situ.

The simplicity of water evacuation plans and their compatibility with the rainwater withdrawal (downpipes diameters and gutters) will make a building less vulnerable and therefore more durable (Expert #1).

Situations with steep roof plane can adversely affect their conservation status; the wind effect can be very damaging. Therefore, the ideal situation would be find a balance between risk and vulnerability. The roof is clearly one of the main sources

ID76 - Ermita Ntra. Sra. de Guía
$v2 = 2.00$
$FBSL = 61.009$

ID15 - San Juan Bautista
$v2 = 4.50$
$FBSL = 41.013$

ID53 - San Marcos
$v2 = 7.50$
$FBSL = 34.484$

Fig. 6. Different evaluations for the different types of roof design and their influence in the FBSL index.

> of moisture in buildings. Not only the design could be decisive, the rainfall region is also totally relevant (Expert #2).

Fig. 6 presents three examples of the evaluation of the roofs design (as defined in Table 1), showing their influence in the output of the model (in the FBSL index). The examples show that more complex roofs present higher evaluation of the $v2$ variable and lead to lower functionality indexes. However, this analysis must be cautious, since the FBSL model is based on a fuzzy inference system, in which 17 input parameters are correlated in an intricate system of "if-then" rules. Therefore, the correlation between the roofs' design and the functionality index is not direct, due to the complexity of the loss of functionality phenomena, which is conditioned by several variables that act synergistically.

In Fig. 7 it is possible to identify pathological situations in the wood structure of the roof over time. Some pictures showing the conservation condition of the Los Sagrados Corazones church before and after intervention in 2008 are provided. The situations related with the presence of humidity by infiltration on the roof structure had several consequences in the state of conservation (v_5) of the built heritage. The roof is one of the elements with the most complex constructive techniques. Thus, the repair and maintenance actions in these elements should be carefully analysed, even more in this kind of heritage buildings, which have suffered all kinds of modifications and live loads (r_7) since their initial construction to the present day. One of the experts consulted refers that:

> The use of the space, both of people and furniture and furnishings, affects the durability of the building and can jeopardize it. Altering the level of use may result in deformations and structural problems. Simultaneous live loads and storage or other uses significantly and negatively affect the durability of a building (Expert #3).

In that sense, it is possible to conclude that buildings with simpler constructive systems characteristics (v_4) are less vulnerable:

> The simplicity and homogeneity of a constructive system also lead to architectural consistency. Complex structures are usually poorly maintained (Expert #4).

In some cases, when the building's roof is perfectly designed in relation to the drainage of water (r_{12}), increasing the slope of the roof can increase the buildings vulnerability to other risks, e.g. the wind effects. Therefore, it is necessary to reach a balanced solution, trying to minimize the risks and vulnerabilities, maximizing the functional service life of the built heritage.

Concerning the variable "geological location" (v_1), the Spanish Geological and Mining Institute (IGME) [67] establishes the criteria for the classification related with the constructive conditions in each region. As mentioned by one of the 15 experts consulted:

> The knowledge regarding the ground transmitting and receiving loads is essential to the design and calculation of the foundation, which is an important factor for the overall durability of a building (Expert #5).

The factor related with environmental conditions (v_3) is also very relevant. It is related with the building context, i.e. buildings with constructions next to them present higher vulnerability indexes, since some interventions in adjacent buildings (such as demolitions or works in the foundations) can compromise their performance. Furthermore, some external agents have a huge impact on the building's functionality. The presence of water is one of the main degradation agents. Regardless of the building's structural characteristics, and how low the vulnerabilities are, the main degradation agent is always the presence of water in all its forms [63].

Fig. 8 present various examples of raising damp in the building analysed: Fig. 8A shows the deterioration of external floor of the building due to the presence of moisture due to capillarity phenomena (with the presence of efflorescence in the lower part of the outer wall); Fig. 8B presents the detachment of the painting of the external facade due to the combined effect of wind, damp and temperature variations; Fig. 8C presents moisture stains and the presence of efflorescence in specific areas of the external wall and on the floor; and Figs. 8D and E show the presence of biological colonization in the socle and the detachment of the external layer of paint and also the detachment of the rendering. During the visual inspection of the building, variable $v5$ (preservation) should be evaluate based on the overall conservation condition of the building, taking into account different parameters such as the deterioration of the foundation, the structure, the facades, the watertightness, installations, and other elements that are relevant to describe the deterioration state of the building. Therefore, the pathological situations identified in Fig. 8 were taken into account for the quantification of variable $v5$, being reflected in the FBSL index achieved for this case study.

Regarding other external risks, the risk of fire is very relevant and challenging for historic buildings. Churches are

(Before intervention)

(After intervention)

Fig. 7. Roof design of the building before and after the intervention in 2008.

extremely vulnerable to this risk, since they contain various ignition sources, and at same time usually do not have an operational fire protection system [64]. Therefore, monitoring and maintenance measures should be implemented in order to reduce these risks to cultural heritage. The expert survey reveals that:

> The possibility of a fire (r_{10}) and, especially the speed and intensity of propagation, is a relevant risk factor, which should be analysed. In some cases, the damage caused by fire can immediately leads to the collapse and destruction of the construction (Expert #6).

The anthropogenic risks are also important; the increase or decrease of the population (r_{14}) can affect the potential number of people that use the church. The experts consulted refer the following regarding the anthropic risks variables (r_{14}), the heritage value (r_{15}) and the occupancy level (r_{17}):

Fig. 8. Pathology observed in the building mainly due to raising damp.

> The functionality of a building is related with factors such as use and maintenance. The legal protection of a building will determine a greater willingness of individuals or entities, public or private, committed to their conservation and durability. The historical or cultural value could be conditioning for the prioritization of interventions. An inhabited and well-preserved building with moderate use will be the most durable one (Expert #7).

The discussion of the results and the comments from the professional expert survey can provide basic information on the decisions taken on when to undertake maintenance works on the churches analysed. An efficient evaluation of the serviceability of cultural buildings must bear in mind several factors that enable optimizing the inspections, maintenance programs and the implementation of a more rational management of the resources spent on constructions during their functional service life.

6. Conclusions

The methodology proposed in this study was developed as a basic instrument for predicting the functional service life of building components in failure conditions for maintenance purposes. The models and results achieved can be very useful in the management and organization of preventive maintenance-oriented activities in buildings, taking into account the financial, social and environmental needs, since the built heritage is an important issue in terms of preserving the culture of the current societies.

In this study, the functional service life of 100 churches in Andalusia was determined based on a fuzzy inference system model. A simplified model based on a multiple linear regression analysis is also proposed, simpler and easier to apply in practical situations, which allows identifying the main variables that have influence on the functional service life of the churches analysed. The proposed models allow obtaining coherent and accurate results, showing a strong correlation between the observed values (based on an expert survey) and the values predicted by the proposed models. In this study, it is found that the roof's design is the most relevant variable for the definition of the end of the functional service life of churches. The analysis of the historical data regarding the interventions carried out during the last decades reveal that, in the majority of the churches analysed, the roof's degradation is itself enough for the decision of intervene. The occupancy, live loads, environmental conditions, population growth and preservation condition are also very relevant variables. As expected, churches more vulnerable and subjected to higher risks present lower functionality indexes, requiring a large number of interventions over the years.

The proposed methodologies intend to be simple and cost-effective tools to determine the functional service life of monuments in a whole region, establishing a prioritization of the maintenance operations in groups of monuments with similar constructive characteristics trying to focus the attention on the buildings with lower functionality levels (with a FBSL index under 34, which require higher conservation efforts and urgent interventions). This approach provides some guidance regarding the risks and vulnerabilities that should be carefully analysed in order to minimize the degradation of cultural heritage and their risk of failure. This study involves an on-site diagnosis analysis balanced by expert's opinion, thus requiring an adapted procedure for other types of buildings. In fact, with the adequate adaptations, the proposed model can be easily implemented in other religious buildings outside of Seville region and other sets of buildings with homogeneous characteristics. To ensure the accurate application of the fuzzy inference system it is recommended to perform a new expert survey to adapt some of the input variables to the regional context of the buildings under analysis.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.culher.2017.03.004.

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