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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 $\mu$ 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 $\mu_A$, $U$ 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

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