Proceedings of the 16th International Conference on Computational and Mathematical Methods in Science and Engineering, CMMSE 2016
4–8 July, 2016.

Time Series on Functional Service Life of Buildings using Fuzzy Delphi Method

A. J. Prieto[1], María-José Chávez[2], María A. Garrido-Vizuete[2], J. M. Macías-Bernal[1] and Daniel Cagigas-Muñiz[3]

[1] *Department of Architectural Construction II, University of Seville*

[2] *Departamento de Matemática Aplicada I, Universidad de Sevilla, Spain*

[3] *Department of Architecture and Computer Technology, University of Seville*

emails: `andpriiba@alum.us.es`, `mjchavez@us.es`, `vizuete@us.es`, `jmmacias@us.es`, `dcagigas@us.es`

Abstract

The functional service life of heritage buildings, defined as the time period during which the building fulfils the requirements for which it was designed, is a complex system that has still not been fully resolved and continues to be the object of research regarding its social, economic and cultural importance. This paper presents an application for analysing time series that reflect the state of building performance over time. To this end, historical time records are used that provided data that could be interpreted by experts in the field. The latter can then evaluate the input variables (vulnerability and risk) using the expert system for predicting the service life of buildings, Fuzzy Building Service Life (FBSL), this methodology put together the fuzzy logic tools and Delphi method. This model provides output data on the state of functionality or performance of each buildings at each moment in time whenever information records are available. The Delphi Method is used to eliminate expert subjectivity, establishing an FDM-type assessment methodology that effectively quantifies the service life of buildings over time. The application is able to provide significant data when generating future preventive maintenance programmes in architectural-cultural heritage buildings. It can also be used to optimise the resources invested in the conservation of heritage buildings. In order to validate this system, the FDM methodology is applied to some specific building examples.

Key words: Functional service life, Fuzzy Delphi Method (FDM), Expert system, Preventive conservation, Architectural heritage, Time series analysis

 ISBN: 978-84-608-6082-2

1 Introduction

The current economic situation has meant that resources intended for building maintenance programmes are fairly limited. As a result, there has been an increase in the number of studies focusing on how to prioritize the need for maintenance work during the service life of buildings. The aim of such studies is to estimate the moment when preventive maintenance actions or programmes need to be performed in buildings, since this type of work can considerably minimise the economic costs of conservation over time. According to the ISO 15686: 2011 international standard [18], service life can be defined as the period of time during which the building and its constituent parts fulfil the requirements for which they were designed, considered as a complex system composed of several sets of *interconnected* variables and whose links create additional information as a result of interactions. Haagenrud (2004) [2] described the number of agents causing deterioration (vulnerability and risk) that have direct and indirect consequences in terms of building maintenance and repair costs. On the other hand, the definition of the end of service life is a subjective concept that depends on criteria that may change over time.

In 2012, Macías-Bernal, Calama and Chávez presented the FBSL (Fuzzy Building Service Life) expert system [6] based on the theory of fuzzy sets [14] and intended for the diagnosis of building service life, the aim being to make predictions based on the concepts of the inherent vulnerability of buildings and external risks, where building performance in functionality terms is the output variable. This model, which will be explained briefly at the end of this section, is able to prioritize preventive conservation actions in groups of buildings with homogeneous architectural features. The FBSL system has recently been declared as compliant with the ISO 31000 : 2009 international standard [19] and the European standard EN 31010 : 2011 [20], both regulatory risk management standards and identified by the Institute of Cultural Heritage of Spain (IPCE) as useful tools for designing preventive conservation plans and risk management in heritage buildings [11]. The FBSL system has also been tested and correlated with another international model used to measure the physical degradation of materials [16] [17].

The traditional Delphi method developed by Dalkey and Helmer [1] (1963) has been widely used to obtain a steady stream of responses based on the results obtained through questionnaires.

It is one prospective method that seeks to obtain the consensus of a panel of experts based on the analysis and reflection of a well-defined problem [3]. It has three main features: anonymous reply, iteration and feedback controlled according to the statistical analysis of a group response.

It requires a long period for implementation since repeat surveys must be conducted in order to eliminate expert subjectivity and obtain uniform conclusions. On the other hand, and depending on the properties studied, it is common for the judgement of experts not to be adequately reflected in quantitative terms.

 ISBN: 978-84-608-6082-2

This is the case of the variables that affect the service life of a building; whenever there is certain ambiguity in their interpretation, it is more desirable for the panel of experts to reflect their preferences using linguistic terms such as "good", "very good", "average", "bad" or "very bad". These linguistic labels will subsequently be processed by fuzzy logic.

This combination between the theory of fuzzy sets and the Delphi method was proposed by Murray, Pipino and Gigch in 1985 [8] and was called the Fuzzy Delphi Method (FDM) [4].

The most important contribution of this study is the application of the FDM methodology for the analysis of historical-time records of buildings by a panel of experts using the FBSL model.

The Fuzzy Buildings Service Life (FBSL) expert system to be identified can be represented as a multi-input non-linear model: $\hat{y} = f(v(x))$, where $v(x)$ is a vector obtained from input data. In this case, the vector for each building x is the input data of the process:

$$v(x) = [v_1(x), v_2(x), \ldots, v_n(x)]$$

where $\{v_i, i = 1, \ldots, n\}$ are input variables. For the estimation of the service life to building x, the model can be represented by:

$$\hat{y}(x) = f(v(x))$$

The FBSL system has been developed following the steps established by Xfuzzy 3.0. [9] in which it is implemented: linguistic variables (input variables and output variables), rule bases and the hierarchical structure that makes up the system. To define the input parameters - specifically factors of vulnerability, static-structural, atmospheric and anthropic risk -, the following documents were reviewed: National Cathedral Plan; Law on Construction Planning: Rehabimed Method; Heritage Conservation Network; Spanish Technical Building Code; UNE 41805 : 2009 IN; ISO 15686 [6]. As a result, a total of 17 input factors (vulnerabilities and risk factors) were validated and ranked. With the collaboration of 15 professional experts in maintenance and building preservation, these factors were validated. A Delphi methodology using Opina software the property of the University of Seville was used to obtain all the experts' answers. The input variables are fuzzified in membership functions $\mu_A(v)$, in which a fuzzy set can take any value in the range of [0,1].

$$\mu_A(v) : \mathrm{U} \rightarrow [0, 1]$$

Gaussian-type membership functions are generally used, as they are considered the most appropriate, reaching a non-zero values at all points. This occurs in all the membership functions of the FBSL fuzzy inference model, except in the membership function of input variable v_1 - Geological location, whose applied membership function is trapezoidal

 ISBN: 978-84-608-6082-2

(established for four types of terrain). The fuzzy inference system uses the fuzzy operator "and" as a connector, which is defined as an intersection. Thus, given two sets A and B, defined on their respective universes of discourse U, the intersection of both sets is a fuzzy set $A \wedge B$, whose membership function is defined in equation (1):

$$\mu_{A \wedge B}(v_i, v_j) = T(\mu_A(v_i), \mu_B(v_j)) \tag{1}$$

where $T(x, y) = min(x, y)$ is a T-norm [13]. The fuzzy BSL system uses the minimum as connective [7].

It is well known that the core of a fuzzy system is the knowledge base comprised of two components: the data base and the rule base. The data base contains the definitions of the linguistic labels, i.e. the membership functions for the fuzzy sets. The rule base 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. In the composition of fuzzy propositions, the min-max or Mamdani inference mechanism is used [7]. This type of method works with the minimum operator as the implication function and the maximum as the aggregation operator [12]:

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

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. The defuzzification method (the mechanism that allows the significant value discreetly representing a fuzzy set to be obtained) used by the FBSL system is the one from the Centre of the area of fuzzy set B, also known as the Centre of Gravity or Centroid [5]; it uses the centre of the area of fuzzy set B as a proxy value, $\hat{y}$. Its discrete version, which can be interpreted as a Riemann sum.

$$\hat{y} = \frac{\sum_i v_i \cdot \mu_B(v_i)}{\sum_i \mu_B(v_i)}$$

The positive properties of this method are, most notably, its continuous nature (a small change in the inputs does not imply an abrupt change in the outputs) and its non-ambiguous nature (it obtains a single value as a result of the process).

 ISBN: 978-84-608-6082-2

2 Delphi Fuzzy Methodology for the historical-time analysis of buildings

It is well known that modelled time series have been designed to develop an effective methodology that conforms to reality and is easy to interpret. These models are considered to be very useful applications in many scientific fields (industrial engineering, business, economic activities, etc.).

The collection of historical time series records is essential when optimising maintenance actions in buildings. The historical-time series of a building is formed by sets of data stored at different moments in time; each of these moments may be formed by one or more data records. Indeed, sometimes there are "windows" in the time series in which a single record does not give a clear and accurate idea of the state of conservation of the building; in these situations, all the accumulated data would constitute a single moment. Prieto, Macías-Bernal and Chávez (2015a) [10] took a first step in this direction by analysing the functionality of buildings through historical records. As a result, milestones were identified that significantly reduced the conservation status of the buildings studied.

Each of the professionals (i_k) belonging to the panel of experts entrusted with interpreting the different historical-time moments (y_h) of each building (x_l) in the round (j_q) will value the input variables of the FBSL: five variables of vulnerability (v_1-Geological location, v_2-Roof design, v_3-Environmental conditions, v_4-Constructive system, v_5-Preservation); 12 risk (r_6-Load state modification, r_7-Dead and live loads, r_8-Ventilation, r_9-Facilities, r_{10}-Fire, r_{11}-Inner environment, r_{12}-Rainfall, r_{13}-Temperature, r_{14}-Population growth, r_{15}-Heritage value, r_{16}-Furniture value, r_{17}-Occupancy), obtaining a Functionality Index generated by the fuzzy expert system. See Equation 3, where j_q is each round in the Delphi methodology.

Each variable involved in the historical-time application of the $FBSL_{i,j}(v(x,y))$ is described below:

$$\hat{y}(x_l, y_h) = FBSL_{i_k,j_q}(v_1(x_l, y_h)), \dots, v_5(x_l, y_h), r_6(x_l, y_h) \dots, r_{17}(x_l, y_h)) \tag{3}$$

- **Set of buildings** $\{x_l, l = 1, \dots, n_1\}$

  The sample of case studies selected must be a set of buildings with uniform construction characteristics to which the 17 vulnerability and risk variables of the FBSL functionality model can be adapted. The validity of the expert system was compared dividing the buildings into two groups [6] [11] [15].

- **Moment** $\{y_h, h = 1, \dots, n_2\}$

  The moments are made up of one or more data records. The data records may have very different characteristics and include historical pictures, paintings, engravings, construction reports, budgets, records of events, records in text format. Historical

 ISBN: 978-84-608-6082-2

data may contain many unique characteristics. For this reason, since the information is primarily qualitative, it is conditioned by great subjectivity when interpreted by expert professionals. Note that the methodology requires a minimum number of time points to be efficient.

- **Panel of experts** $\{y_k, k = 1, \ldots, n_3\}$

  For the experts to be able to carry out the DFM methodology, they must not know each other and there must never be a possibility for them to interact. They undertake to take responsibility for making judgements and opinions, which are the cornerstone of the method. Their profiles must cover different areas of knowledge related to the field of construction, including architecture, heritage conservation and building surveys.

  The number of experts also depends on the budget available for each study. It is generally considered that the number of experts should not be less than 7 and not more than around 30.

- **Round** $\{j_q, q = 1, \ldots, n_4\}$

  The experts are responsible for interpreting the data over the historical time series by iterating questions and answers in each *rondas* (j_q) on which the FDM method is based. A *process coordinator* group receives the responses generated in each stage. As the rounds are completed, the degree of reliability of the answers provided by the experts increases, thus generating a base of increasingly objective and reliable knowledge. As many iterations as necessary are performed among the experts to obtain sufficiently objective conclusions.

  After the action in the first round, the coordinating group calculates the appropriate statistical centralisation and dispersion parameters to observe those information records for which a fuzzier value from the experts is obtained, resulting in the drafting of the questionnaire for the next round.

3 Results and discussion

To illustrate the use of our methodology, we considered the following 20 heritage buildings located in the province of Seville (Spain).

The buildings were religious buildings with heritage features built between the 15th-16th centuries. They had other uniform political, cultural and social features. However, the chronology and stylistic characteristics of the Mudéjar buildings in the province of Seville made every building unique. Each of these buildings is located in the urban area of the corresponding locality and none are in a state of ruin or neglect [6].

A total of around 400 data records exist for the period from 1400 to the present. These include prints, paintings, photographs, records of information from newspaper archives,

 ISBN: 978-84-608-6082-2

manuscripts from parish archives dating from different periods describing interventions, restoration work or even possible consolidation work in the buildings, as well works certificates in the case of more recent buildings.

A group of 10 professional experts with profiles relating to the fields of Chemical Sciences, Architecture, Construction, Environment, Restoration and History were entrusted with assessing the 17 input variables of the FBSL by interpreting each of the records stored at each moment of time. Figure 1 shows the results obtained by one expert in the first round.

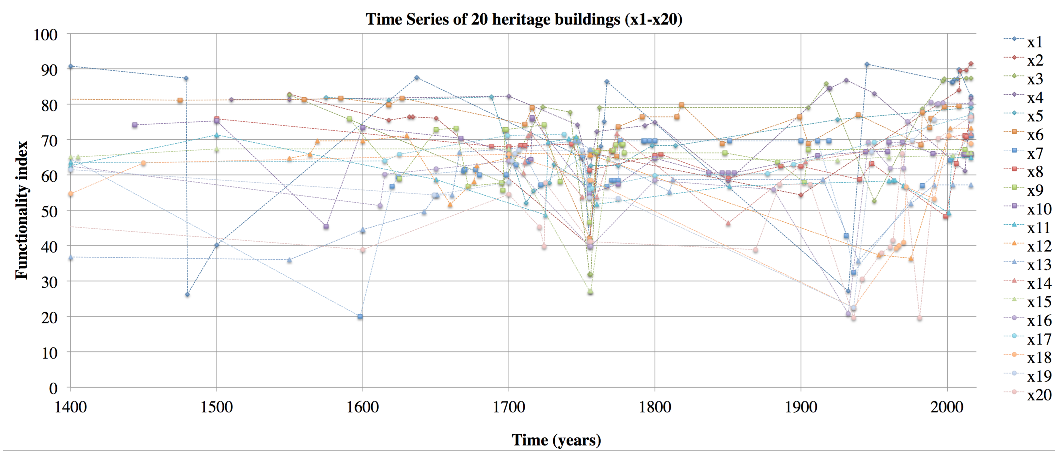

Figure 1: Historical evolution of the functionality of the uniform set of heritage buildings located in the province of Seville between 1400-2016.

As a specific case, the San Pablo Parish Church in Aznalcázar was chosen for analysis and individual representation.

In the time analysis of the San Pablo de Aznalcázar Parish Church (x_1), a total of 22 historical records dating from between 1400 and 2016 were recovered. Data collection was difficult. The historical time series data in this study were gathered manually from the parish archives owned by the Archdiocese of Seville. It was also essential to analyse the photographs that were recovered (University of Seville photographic library) as they reveal reliable information on the functional state of the building, and can also be easily compared with qualitative records in text format.

After analysing this information (see Figure 2), three unique events were identified as having had a significant influence on the functional level of the building: the first fire in the building (1480), the Lisbon earthquake (1755) and the second fire in the building four years before the Spanish Civil War (1932).

 ISBN: 978-84-608-6082-2

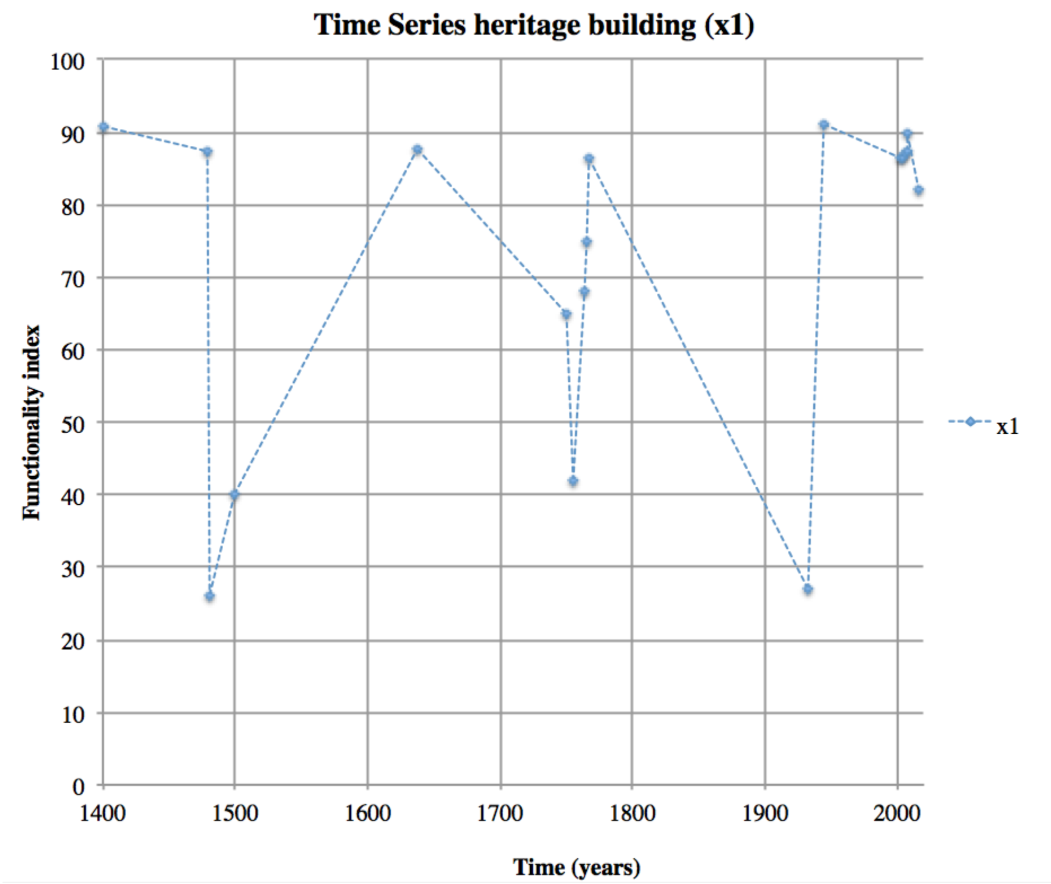

Figure 2: Historical evolution of the functionality of San Pablo de Aznalcázar parish church from 1400 to 2016.

 ISBN: 978-84-608-6082-2

4 Conclusions

The overall importance of sustainable development requires appropriate decisions to be taken to guarantee the service life of buildings. To achieve this, it is necessary to establish tools that can be used to define conservation and preventive maintenance plans and enhance building performance.

A new FDM-based methodology for the prediction of the service life of buildings over time by means of the analysis of historical time series is presented. This model requires records of information gathered to define the historical moments in the best possible way, and therefore achieve a better definition of building functionality. Moreover, the system is also able to effectively identify significant milestones that have compromised the life of the buildings over time.

The knowledge gathered in this study can be used to develop new methodologies based on the historical-temporal information stored and to support the taking of decisions regarding the best time to perform maintenance work, as well as to limit maintenance costs.

In terms of work in progress, FDM is currently being used in homogeneous sets of heritage buildings in southern Europe, Spain and Portugal.

This study can be extended to other buildings and other construction elements located in other regions of Europe. However, in order to carry out this application, the model must be adapted to the actual characteristics and circumstances of each location. In this sense, the analysis of the sensitivity of the model may be useful for defining and adjusting the different input variables that influence the system in order to improve the desired results and conclusions.

 ISBN: 978-84-608-6082-2

Acknowledgements

The authors gratefully acknowledge the support of Ministerio de Economía y Competitividad de España, Project ART-RISK - BIA2015-64878-R, Project MTM 2015-65397-P.

References

[1] N. Dalkey and O. Helmer, *An experimental application of the Delphi method to the use of experts*, Management Science **9** (1963) 458–467.

[2] S. E. Haagenrud, *Factors causing degradation. Guide and bibliography to service life and durability research for buildings and components, Joint CIB W80/RILEM TC 140*, Prediction Service Life Building Materials Components **2** (1-2) (2004) 105.

[3] C. L. Hwang and M. J. Lin, *Group decision making under multiple criteria: Methods and applications*, Springer-Verlag, 1987.

[4] A. Ishikawa, M. Amagasa, T. Shiga, G. Tomizawa, R. Tatsuta, and H. Mieno, *The max-min Delphi method and fuzzy Delphi method via fuzzy integration*, Fuzzy Sets and Systems **55** (1993) 241–253.

[5] R. Jager, H. B. Verbrugen and P. M. Bruhx, *The role of defuzzification methods in the application of fuzzy logic*, Symposium on Intelligent Components and Instruments for Control Applications (1992), Málaga, Spain.

[6] J. M. Macías-Bernal, J. M. Calama and M. J. Chávez, *Modelo de predicción de la vida útil de la edificación patrimonial a partir de la lógica difusa*, Informes de la Construcción **66**(533) (2014) p.e006.

[7] E. H. Mamdani and S. Assilian, *An experiment in linguistic synthesis with a fuzzy logic controller*, International Journal of Man-Machine Studies **7**(1) (1975) 1–13, D.O.I. 10.1016/S0020-7373(75)80002-2.

[8] T. J. Murray, L. L. Pipino and J. P. Gigch, *A pilot study of fuzzy set modification of Delphi*, Human Systems Management (1985) 6–80.

[9] F. J. Moreno-Velo, I. Baturone, A. Barriga and S. Sánchez-Solano, *Automatic tuning of complex fuzzy system with Xfuzzy*, Fuzzy sets and systems **158** (2007) 2026–2038.

[10] A. J. Prieto, J. M. Macías-Bernal and M. J. Chávez, *Series Temporales de Factores Principales para la Conservación Preventiva del Patrimonio*, 5º Congreso de Patología y Rehabilitación de Edificios (2015a), Porto, Portugal, ISBN: 78-972-752-177-7.

[11] A. J. Prieto, J. M. Macías-Bernal, M. J. Chávez and F. J. Alejandre, *Expert system for predicting buildings service life under ISO* 31000 *standard. Application in architectural heritage*, Journal of Cultural Heritage **18** (2015b) 209–218.

[12] T. J. Ross, *Fuzzy logic with engineering applications*, John Wiley & Sons, 2010.

[13] S. Weber, *A general concept of fuzzy connectives, negations and implications based on t-norms*, Fuzzy Sets and Systems **11** (1983) 115–134.

[14] L. A. Zadeh, *Fuzzy sets*, Information and Computation **8**(3) (1965) 338–353.

[15] A. J. Prieto, A. Silva, J. de Brito and F. J. Alejandre, *Functional and physical service life of natural stone claddings*, Journal of Materials in Civil Engineering **Article In Press** (2016)

[16] P.L̇. Gaspar and J. de Brito, *Service life estimation of cement-rendered facades*, Building Research and Information **36**(1) (2008) 44–55.

[17] J. L. Dias, A. Silva, C. Chai, P. L. Gaspar and J. de Brito, *Neural networks applied to service life prediction of exterior painted surfaces*, Building Research and Information **42**(3) (2014) 371–380.

[18] ISO, *Building Construction - Service Life Planning - Part 4: Service Life Planning using Building Information Modelling, ISO 15686-4, 2014, pp. 2014*,

[19] ISO, *Risk Management - Principles and Guidelines, ISO 31000, 2009, pp. 2009.*

[20] UNE EN ISO/IEC 31010, *Risk Management, Risk Assessment Techniques Focuses On Risk Assessment. Risk Assessment Helps Decision Makers Under- stand The Risks That Could Affect The Achievement Of Objectives As Well As The Adequacy Of The Controls Already In Place, 2011.*

 ISBN: 978-84-608-6082-2