Preventive Conservation and Restoration Monitoring of Heritage Buildings Based on Fuzzy Logic

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ABSTRACT

This article discusses the usability of the Art-Risk 3.0 software for research on the conservation of heritage buildings. It is a new and free software based on fuzzy logic, which enables the assessment of preventive conservation and surveillance of the restoration of heritage buildings over a period of time. This artificial intelligence-based tool considers the vulnerability of buildings, their environments, and their management to evaluate the necessity of their restoration or preventive conservation. To validate the Art-Risk 3.0, 500 theoretical case studies were analyzed, and a 14th-century Mudejar-Gothic-style Church in Seville, Spain was studied both before and after its restoration to identify post-restoration changes. This proof of concept demonstrates the capability of the Art-Risk 3.0 software to analyze environmental impacts on the vulnerability, risk, and functional service life of buildings, and assess the effectiveness of restoration activities. Additionally, this software identifies the most problematic factors and the necessity of restoration.

KEYWORDS

Functionality; fuzzy logic; heritage; risk; service life; vulnerability

1. Introduction

Risk for buildings, which is understood as potential losses, is a term closely linked to the existence of threats and the vulnerability of an environment. As a quantifiable phenomenon, risk is susceptible to changes depending on modifications made in a specific place and time period (UNISDR 2009). It is possible to reduce the risk level of a context by reducing the degree of vulnerability or improving environmental conditions.

In the case of heritage buildings, implementing risk management policies makes it possible to avoid exposing heritage assets to high levels of risk and minimize the consequences of a threat (ICOMOS 2020; UNESCO-WHC 2012; UNDRR, n.d.). In recent years, within the framework of preventive conservation, numerous studies have analyzed the risks to a heritage assets (Arrighi et al. 2018; De Masi et al. 2021; Despotaki et al. 2018; Elfadaly, Attia, and Lasaponara 2018; Gerardo, Salazar, and Ferreira 2020; Maio, Ferreira, and Vicente 2018; Salvo et al. 2018; Sardella et al. 2020; Stephenson and D'ayala 2014; Toth 2018).

Despite the existence of practical studies for the individual evaluation of a threat (Bonazza et al. 2018; Sardella et al. 2020; Toth 2018), the development of multi-risk studies which globally assess all the risks present in an environment is a major setback in the research. Recently, multicriteria-models, have conducted a comprehensive analysis of all existing threats in outdoor spaces (Borg et al. 2014; Brimblecombe, Hayashi, and Futagami 2020; Lombardo, Tanyas, and Nicu 2020; Sabbioni, Brimblecombe, and Cassar 2010; Saha et al. 2021; Sevieri et al. 2020; Valagussa et al. 2020).

Regarding risk assessment, the cultural value associated with heritage assets has been recently included as a variable to consider along with threats and vulnerability (Sesana et al. 2020; Turskis, Morkunaite, and Kutut 2017; UNESCO-WHC 2012) From this framework, the methodological model proposed by Sevieri et al. (2020) is especially interesting and proposes the use of *prioritization indices* that take into account the natural hazards and cultural value of heritage assets.

Furthermore, although it is accepted at a theoretical level that the risk affecting cultural heritage can be mitigated via conservation and maintenance policies (Jigyasu 2020; Stanton-Geddes and Soz 2017), most risk models do not analyze these variables. Consequently, existing risk models calculate a static concept of vulnerability that does not consider the *adaptive capacity of heritage* (Sesana et al. 2020). In response

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to this problem, many studies have proposed quantifying vulnerability based on the building's state of conservation (Ruiz-Jaramillo et al. 2020; Sánchez-Aparicio et al. 2020) and the use of *risk damage prediction indices* (Fabbri and Bonora 2021; Makoond, Pelà, and Molins 2021).

The methodology developed by the *Art-Risk* project is a significant example of a multi-scenario risk analysis tool that combines the assessment of environmental threats, vulnerabilities, cultural value and conservation policies (Ortiz and Ortiz 2016).

The *Art-Risk* 3.0 models raised the possibility of identifying and quantifying the variables that influence the levels of risk registered in a building. The predictive model enables potential users to analyse, understand and quantify complex risk scenarios for heritage structures (Ortiz et al. 2014; Ortiz, 2014; Ortiz and Ortiz 2016; Rodríguez-Rosales et al. 2021; Moreno, Ortiz, and Ortiz 2019). Among its most recent results is *Art-Risk* 3.0, a free and open digital tool that allows the analysis of risk contexts for heritage structures (available in: https://www.upo.es/investiga/art-risk-service/art-risk3/ [last accessed on November 29, 2021]) (Cagigas-Muñiz et al. 2020; Ortiz et al 2019).

The overall objective of this study is to demonstrate that Art-Risk 3.0 presents a similar performance to the approach defined by the fuzzy model (FBSL) previously described by Prieto et al. (2017). This study validates the *Art-Risk* 3.0 fuzzy model by applying it to 500 hypothetical case studies and presents a diachronic risk analysis using the *Art-Risk* 3.0 tool to analyze the changes in vulnerability and functionality due to a restoration process. The case study was conducted at the Santa Catalina Church (Seville, Spain). It covers a period of time from 2012 to 2020 and describes the changes that the restoration conducted in 2018 has brought about in terms of the vulnerability, risks and functionality of the building.

In scenarios of change, as is the case described, the *Art-Risk* 3.0 software is submitted as an option for multi-scenario risk analysis. Owing to the use of artificial intelligence, *Art-Risk* 3.0 enables the quantification of the levels of risk, vulnerability and functionality of a building. Previous models have already been used successfully for the analysis of sets of structures (Cagigas-Muñiz et al. 2019; Ortiz et al. 2019; Prieto et al. 2017; Prieto, Verichev, and Carpio, 2020) and this is the first study to propose its use in multi-temporal studies and analysis of modifications in the levels of vulnerability-risk that a building presents over time.

2. Materials and methods

2.1. Fuzzy logic model

The fuzzy logic theory has been extensively applied as an instrument for decision-making processes in engineering areas such as the service-life prediction of façade claddings (Silva, De Brito, and Gaspar 2016). This type of methodology is particularly relevant when the problem modelled is subject to a considerable degree of uncertainty. In this sense, fuzzy logic, introduced in 1965 by Zadeh (1965); Zadeh (1978), is an innovative technique to model real-world phenomena.

The new fuzzy model (*Art-Risk*3.0) presented in this research is based on previous experience criteria and has several applications: (i) the Delphi method developed by the University of *Pablo de Olavide* (*Art-Risk* 1.0) (Ortiz et al. 2019; Ortiz 2014,; Ortiz and Ortiz 2016) and (ii) an artificial intelligence-based tool concerning the fuzzy logic system developed by the University of Seville (*Art-Risk* 2.0/$FBSL_{2.0}$) (Macías-Bernal, Calama-Rodríguez, and Chávez-De Diego 2014; Ortiz et al. 2019; Prieto et al. 2017, 2016, 2018). The artificial intelligence-based tool has already been validated and published based on previous approaches concerning the applicability of the fuzzy logic system (Art-Risk 3.0) at a World Heritage Site, the Royal Alcazar of Seville (Spain) (Torres-González et al. 2021) and a set of heritage parish churches emplaced in Popayán (Colombia) (Prieto et al. 2020). The rules in the new fuzzy model were extended and modified in relation to the case of churches in Popayán.

The fuzzification and defuzzification processes of the method have been described in detail by Prieto et al. (2017), Prieto et al. (2020)). The fuzzy system involves four main components or stages: (i) the fuzzification process, (ii) the fuzzy rule base, (iii) the fuzzy inference engine, and (iv) the defuzzification process.

The *fuzzification process* transforms each crisp input data into degrees of membership using a lookup in several membership functions. In fuzzy logic, the idea is the allowance of partial belonging of any situation to different subsets of a universal set instead of belonging to a single set completely (Thaker and Nagori 2018). Partial belonging to a set is explained mathematically via a membership function, which assumes that values between 0 and 1 included. The membership functions for the set of input variables (10 vulnerabilities and 11 risks) are Gaussian membership functions. In Tables 1 and 2 the 21 input variables of the model are described concerning their qualitative and quantitative valuations.

Regarding the input parameters (Ar1 — Geological location until, Ar10), these are connected to the output variable — vulnerability. Likewise, from Ar11 —

Table 1. Input variables related to vulnerability: constructive vulnerability, anthropic affections and maintainability.

Ids	Input variables	Quantitative valuation (1: very good/ 5: very bad)	Qualitative valuation	Categories
Ar1	Geological location	[1,2,3,4,5]	Very favorable/very unfavorable ground conditions	Constructive vulnerability
Ar2	Built environment	-	Buildings without or between complex surrounding constructions.	
Ar3	Construction system	-	Uniform or heterogeneous characteristics of the construction system.	
Ar9	Roof design	-	Fast or complex and slow evacuation of water.	
AR10	Conservation	-	Optimal neglected state of conservation.	
Ar4	Population growth	[1,2,3,4,5]	Population growth greater than 15% (favorable)/less than 5% (unfavorable).	Anthropic affections
Ar5	Heritage value	-	Great/low historical value.	
Ar6	Value of movable assets	-	High/low furniture value.	
Ar7	Occupancy	-	High/low activity in the building.	
Ar8	Maintenance	[1,2,3,4,5]	Good/bad maintenance of the building	Maintainability

Ventilation until Ar19 Frozen damage, these variables are linked to external risk assessment. Figure 1 describes the relationship between the input, intermediate and output variables of the fuzzy logic model. Thereafter, all input parameters generate the output functional service life of buildings/structure, which makes up by the previous set of vulnerability and risks parameters. To standardize the qualitative valuation of the input variables, the Art Risk 3.0 tool includes the data entry manual (Proyecto de Investigación ART-RISK Cooperación 2020) and a card model (Ortiz et al.2019) (Figure 1). The manual provides a brief description of each of the input variables and specifies the ranges and evaluation criteria to be followed. The values assigned to the static-structural hazards were obtained using of linguistic indicators (Figure 1). The tool includes graphic descriptors to quantify constructive vulnerability variables (Figure 1). The heritage value of a building and the value of its movable assets are based on its social, cultural, and liturgical perceptions, which are reflected in the building's cataloging and the degree of legal protection. These criteria have been defined by a multi-disciplinary group of heritage experts and correspond to the variables currently used in similar risk assessment studies (Kjølsen Jernæs 2021; Ruiz-Jaramillo et al. 2020; Sánchez-Aparicio et al. 2020; Sevieri et al. 2020; UNESCO-WHC 2012). Environmental and natural hazards were automatically obtained from a geographic information system included in the Art-Risk 3.0 tool

The fuzzy rule base includes a set of fuzzy inference rules established by experts who participated in the design stage. These rules are described using the IF-THEN statement format. In this fuzzy system, all uncertainties including linear and nonlinear relationships are defined in the descriptive fuzzy IF-THEN procedures (Jantzen 1998).

This model is defined using a type of Mamdani fuzzy rules related to input and output variables. In the Mamdani fuzzy inference rules (Mamdani and Assilian 1975), the consequences of the base set of rules are calculated based on the opinions of professional experts (Kothamasu and Huang 2007).

Delphi is a multi-criteria decision-making method frequently used in the assessment of cultural heritage (Morkūnaitė, Kalibatas, and Kalibatienė 2019; Ramalhinho and Macedo 2019). In the Delphi method, a group of experts complete a questionnaire about a complex problem. It is developed in a sequence of two or more rounds until a unique value for each question is reached. In the first round, the experts answer according to their professional experience and background. For the next round/s, each member receives a feedback with the average of the answers given by the other experts and must individually reevaluate their answers. Its main advantage is that it allows an expert response to the same topic taking into account different points of view (Ramalhinho and Macedo 2019). Weighted factors were obtained using the double Delphi process with more than seven experts, over the minimum value of individuals for these surveys. According to the literature, most of the articles published with Delphi studies use groups of 11 to 20 experts, as in the model presented (Sossa, Halal, and Zarta 2019).

The fuzzy rules were extracted from constructors, chemists, engineers and architects, considering their experiences and judgments as experts (Table 3). A total of 18 professional experts from Spain, Portugal and Chile were consulted during the design stage following a DELPHI double-round pond. Those consulted possessed an average of 22 years of experience in the heritage buildings management sector (Table 3). This new model uses 693 fuzzy inference rules, which are organized into five levels of intermediate inference. The hierarchical structure of the upgraded fuzzy model (*Art-Risk* 3.0) is shown inFigure 2

The fuzzy inference engine considers all 693 fuzzy inference rules of the fuzzy rule base, which converts crisp input data to corresponding crisp outputs. The Mamdani inference mechanism was applied to compose the fuzzy

Table 2. Input variables related to risk: static-structural, environmental and natural hazards.

Ids	Input variables	Quantitative valuation (1:very good/5:very bad)	Qualitative valuation	Categories
Ar11	Ventilation	[1,2,3,4,5]	Natural cross-ventilation in all or only in some areas.	Static-Structural hazards
Ar13	Overloads	-	Live load below/higher than the original level.	
Ar14	Fire	-	Low/high fire load in relation to the combustible structure.	
Ar12	Facilities	-	All/some facilities are in use or are not ready to be used.	
Ar15	Structural modification	-	Apparently/disorderly modification.	
Ar16	Average Rainfall	[1,2,3,4,5]	<600mmm(favorable)/>1000 mm(unfavorable).	Environmental hazards
Ar17	Raindrop impact (Torrential rain index)	-	<7(favourable)/>10(unfavourable).	
Ar18	Thermal stress (Thermal amplitude)	-	<6(favourable)/<10(unfavourable).	
Ar19	Frozen damage (days below 0)	-	<1day(favorable)/>60 days(unfavorable).	
Ar20	Seismic hazard (acceleration)	[1,2,3,4,5]	<0.04 g(favorable)/>0.16 g(unfavorable).	Natural hazards
Ar21	Flooding hazard	-	Never(favorable)/10 years(unfavorable).	

propositions. This type of method works with the minimum operator as the implication function and the maximum as the aggregation operator (Chai, Jia, and Zhang 2009). In Table 4 a set of 30 fuzzy rules selected is described as an example.

The defuzzification process transforms the fuzzy outputs from the inference engine to a *number*. A common, successful and prevalent defuzzification method used in this study is the centroid method (Chandramohan, Rao, and Senthil Arumugam 2006). The fuzzy model generates three outputs: (i) the intrinsic vulnerability of the buildings, (ii) the effects of external risks, and (iii) a functionality index, which can to integrate the set of vulnerabilities and risks (Prieto et al. 2020). The *Art-Risk* 3.0 fuzzy method allows users, owners, and public administrations to manage the functional requirements of buildings.

2.2. Case study

The Parish Church of Santa Catalina, a religious temple for Catholic worship, is located in the historical center of Seville (Spain) (Figure 3), at a place where once a Roman temple, a Visigoth church, and later a mosque stood (Ramos 1994). Built in the Gothic-Mudejar style, it underwent modifications throughout the 17th and 18th centuries. In 1912 was declared a *National Monument* and a *Cultural Interest Asset* in 1985.

It was built with brick, lined with mortar, and painted in white and ochre. The church presents three naves, the central one wider and taller than the lateral ones, with a knuckle coffered ceiling in the central nave, and a hanging one on the sides, both in Mudejar style. There is a tribune or choir at the foot of the church's body and on the access opening, and on its sides there are pointed horseshoe blind arches inscribed in other polylobed arched (Ramos 1994). On either side of the choir there is a small room, the one on the left serves as a small library, and that on the right contains a staircase. On the outside, stands the remains of a structure resembling a lapse, the result of a 16th century extension (Antonio Blanco Freijeiro 1992). There is a tower with a Mudejar structure, that initially presents ashlars (Figure 4).

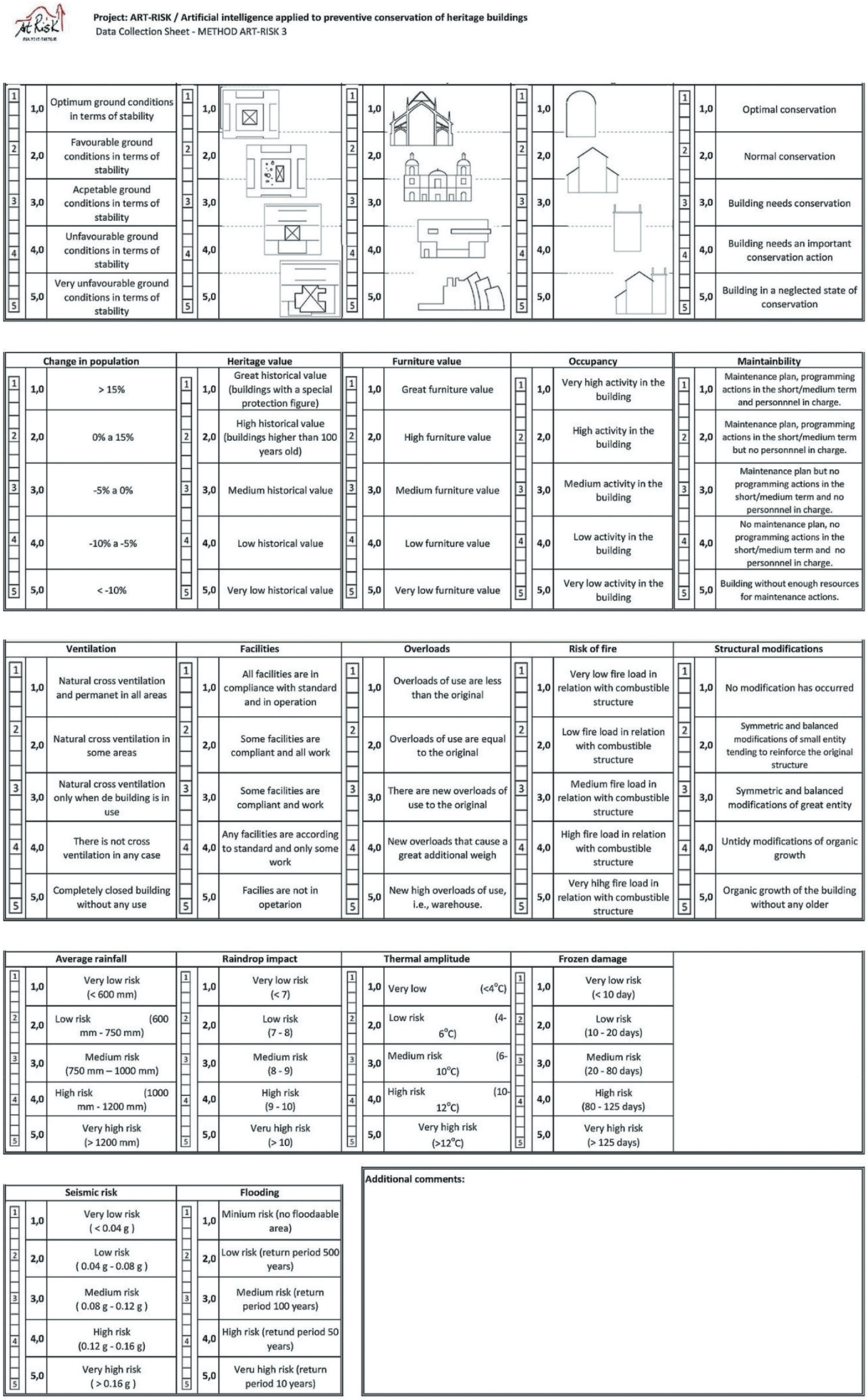
Given its deplorable physical state, the church closed in 2004. From 2009 to 2011 renovation work focused on the restoration of the roof. In 2012, the creation of a perimeter cavity wall began to would improve the natural ventilation of the walls. In turn, archaeological work deepened our historical knowledge of the building. After 14 years, it was reopened in 2018 (Figure 5)) (Macias-Bernal 2010).

2.3. On-site analyses

On-site technical inspections were conducted by an interdisciplinary team of architects and restoration professionals. Technical inspections were performed in 2012, 2019, and 2020. The measurement instruments used were the *Art-Risk* index card model (Ortiz et al.2019) and the *Art-Risk* 3.0 computer tool (Cagigas-Muñiz et al. 2020). Both instruments require the introduction of 21 input variables (Ar1, Ar2, ... Ar21) with values between 1 (very favorable) and 5 (very unfavorable).

The variables of vulnerability and static-structural risks were collected using the *Art-Risk* 3.0 index card. The graphic descriptors included in the index card were used to fill the vulnerability data manually. For the remaining variables, the index card had linguistic descriptors. The data obtained were manually migrated to the *Art-Risk* 3.0 computer tool.

The variables of environmental and natural risks were obtained automatically using *Art-Risk* 3.0. The geographical coordinates of the Santa Catalina Church were identified in WGS84 (37.393161, −5.988127) and were manually entered into the app.



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1,0	Optimum ground conditions in terms of stability	1,0		1,0		1,0		1,0	Optimal conservation
2,0	Favourable ground conditions in terms of stability	2,0		2,0		2,0		2,0	Normal conservation
3,0	Acpetable ground conditions in terms of stability	3,0		3,0		3,0		3,0	Building needs conservation
4,0	Unfavourable ground conditions in terms of stability	4,0		4,0		4,0		4,0	Building needs an important conservation action
5,0	Very unfavourable ground conditions in terms of stability	5,0		5,0		5,0		5,0	Building in a neglected state of conservation

Change in population		Heritage value		Furniture value		Occupancy		Maintainbility	
1,0	> 15%	1,0	Great historical value (buildings with a special protection figure)	1,0	Great furniture value	1,0	Very high activity in the building	1,0	Maintenance plan, programming actions in the short/medium term and personnel in charge.
2,0	0% a 15%	2,0	High historical value (buildings higher than 100 years old)	2,0	High furniture value	2,0	High activity in the building	2,0	Maintenance plan, programming actions in the short/medium term but no personnnel in charge.
3,0	-5% a 0%	3,0	Medium historical value	3,0	Medium furniture value	3,0	Medium activity in the building	3,0	Maintenance plan but no programming actions in the short/medium term and no personnnel in charge.
4,0	-10% a -5%	4,0	Low historical value	4,0	Low furniture value	4,0	Low activity in the building	4,0	No maintenance plan, no programming actions in the short/medium term and no personnnel in charge.
5,0	< -10%	5,0	Very low historical value	5,0	Very low furniture value	5,0	Very low activity in the building	5,0	Building without enough resources for maintenance actions.

Ventilation		Facilities		Overloads		Risk of fire		Structural modifications	
1,0	Natural cross ventilation and permanet in all areas	1,0	All facilities are in compliance with standard and in operation	1,0	Overloads of use are less than the original	1,0	Very low fire load in relation with combustible structure	1,0	No modification has occurred
2,0	Natural cross ventilation in some areas	2,0	Some facilities are compliant and all work	2,0	Overloads of use are equal to the original	2,0	Low fire load in relation with combustible structure	2,0	Symmetric and balanced modifications of small entity tending to reinforce the original structure
3,0	Natural cross ventilation only when de building is in use	3,0	Some facilities are compliant and work	3,0	There are new overloads of use to the original	3,0	Medium fire load in relation with combustible structure	3,0	Symmetric and balanced modifications of great entity
4,0	There is not cross ventilation in any case	4,0	Any facilities are according to standard and only some work	4,0	New overloads that cause a great additional weigh	4,0	High fire load in relation with combustible structure	4,0	Untidy modifications of organic growth
5,0	Completely closed building without any use	5,0	Facilies are not in opetarion	5,0	New high overloads of use, i.e., warehouse.	5,0	Very hihg fire load in relation with combustible structure	5,0	Organic growth of the building without any older

Average rainfall		Raindrop impact		Thermal amplitude		Frozen damage	
1,0	Very low risk (< 600 mm)	1,0	Very low risk (< 7)	1,0	Very low (<4°C)	1,0	Very low risk (< 10 day)
2,0	Low risk (600 mm - 750 mm)	2,0	Low risk (7 - 8)	2,0	Low risk (4-6°C)	2,0	Low risk (10 - 20 days)
3,0	Medium risk (750 mm – 1000 mm)	3,0	Medium risk (8 - 9)	3,0	Medium risk (6-10°C)	3,0	Medium risk (20 - 80 days)
4,0	High risk (1000 mm - 1200 mm)	4,0	High risk (9 - 10)	4,0	High risk (10-12°C)	4,0	High risk (80 - 125 days)
5,0	Very high risk (> 1200 mm)	5,0	Veru high risk (> 10)	5,0	Very high risk (>12°C)	5,0	Very high risk (> 125 days)

Seismic risk		Flooding	
1,0	Very low risk (< 0.04 g)	1,0	Minium risk (no floodaable area)
2,0	Low risk (0.04 g - 0.08 g)	2,0	Low risk (return period 500 years)
3,0	Medium risk (0.08 g - 0.12 g)	3,0	Medium risk (return period 100 years)
4,0	High risk (0.12 g - 0.16 g)	4,0	High risk (retund period 50 years)
5,0	Very high risk (> 0.16 g)	5,0	Veru high risk (return period 10 years)

Additional comments:

Figure 1. Card model for data entry (Art-Risk)

Based on all the variables entered, *Art-Risk* 3.0 calculated three output variables: risk index, vulnerability index and functionality index for each of the analyzed moments in time 2012, 2019 and 2020. These values were interpreted based on the interpretation of results tables provided in the computer tool manual (Ortiz et al.2019).

Table 3. Characterization of the professional experts' survey.

Nº	Professional and academic profile	Country	Years of experience in heritage buildings management
1	Ph.D. in Chemistry	Spain	28
2	MSc. Building Engineer	Spain	5
3	Ph.D. in Building Engineering	Spain	34
4	MSc. Architect	Spain	45
5	MSc. Building Engineer	Spain	33
6	Ph.D. in Building Engineering	Spain	22
7	Ph.D. in Building Engineering	Spain	33
8	MSc. Building Engineering	Spain	5
9	MSc. Building Engineer	Spain	40
10	Ph.D. in Architecture	Spain	17
11	Ph.D. in Building Engineering	Spain	12
12	Ph.D. in Building Engineering	Spain	36
13	Ph.D. in Architecture	Spain	27
14	MSc. Architect	Spain	32
15	Ph.D. in Civil Engineering	Portugal	10
16	MSc. Civil Engineer	Chile	5
17	MSc. Civil Engineer	Chile	5
18	Ph.D. in Building Engineering	Spain	16

Table 4. A selection of if-and-then fuzzy inference rules is presented: VL — Very Low; L — Low; M — Medium; H — High; VH — Very High.

Rule	*RF*	RD	TM	FZ	Environmental risks
1	VL	VL	VL	VL	VL
2	L	VL	VL	VL	VL
3	M	VL	VL	VL	L
4	VL	VL	H	VL	L
5	VH	H	VH	VH	VH
6	H	L	L	L	M
7	VL	M	M	M	L
8	H	H	L	H	M
9	VH	M	VH	VH	H
10	VH	VH	VH	L	M
11	M	H	H	H	H
12	M	M	M	VH	H
13	L	VL	L	VH	H
14	M	M	M	M	M
15	L	H	L	L	M
16	H	L	H	H	M
17	M	M	L	M	M
18	H	VH	H	H	VH
19	H	M	L	VH	M
20	L	L	L	L	L
21	H	M	VH	VH	VH
22	L	L	M	VH	M
23	VL	L	VL	VH	L
24	M	M	M	M	M
25	VL	VH	VL	L	M
26	VH	H	VH	H	H
27	H	H	H	VL	M
28	L	M	M	L	M
29	M	M	H	VH	H
30	VH	M	VH	VH	H

NOTE: RF — Average rainfall; RD — Raindrop impact; TM — Thermal stress; FZ — Frozen damage.

3. Results and discussion

3.1. Functional service life and external risk correlation in 500 theoretical case studies

In this section, the objective of this theoretical application is to understand the variation and behavior of the output variables of the fuzzy logic model (*Art-Risk* 3.0).

The current theoretical approach focused on a set of 500 new case studies that pretended to be meticulous, specific sensitivity analyses of the fuzzy logic model. This application was designed considering several options of the input variables of the system to explain the variability of the output variables of the model, with focus on the functional service life and external risk parameters (Figures 7)

This computational method considers the intrinsic variables of buildings given by vulnerability index — *V* (Ortiz et al. 2019), as well as the consequences of environmental and static-structural conditions given by external risks affection index — *R* and the functional service life of buildings given by functional service life index — *FSL*(Prieto, Verichev, and Carpio 2020). As established by Masters (1985) and recently commented by Tinga et al. (2020), the concept of functional service life is meaningless unless the functional requirements and demands are defined quantitatively (Prieto et al. 2018). Thus, this approach establishes a correlation between functional service life and risks of a set of 500 theoretical case studies. Consequently, it is able to provide information to support decision-making and to optimize preventive maintenance and preventive conservation strategies of heritage buildings. After quantifying the different input variables of the model in the *Art-Risk* 3.0 system, a priority classification of the set of 500 theoretical case studies was obtained. The set of case studies was modeled considering very low to very high functional service life and risks considering minimum and maximum values. The correlation between functional service life index (*FSL*) and external risk affection index (*R*) was established as inversely proportional, which means that lower functional service life indexes correspond to higher risk affection levels, and vice-versa (Prieto et al. 2017).

The values of the 500 analyzed cases were theoretically designed in Excel. The first case study presents the minimum values of risk and vulnerability (1) for all the input variables. The last case study presents the maximum values of vulnerability and risk (5) in each of the 21 variables. The rest of the theoretical cases analyzed correspond to random combinations that assign values from 1 to 5 for each of the 21 input variables. A Pearson

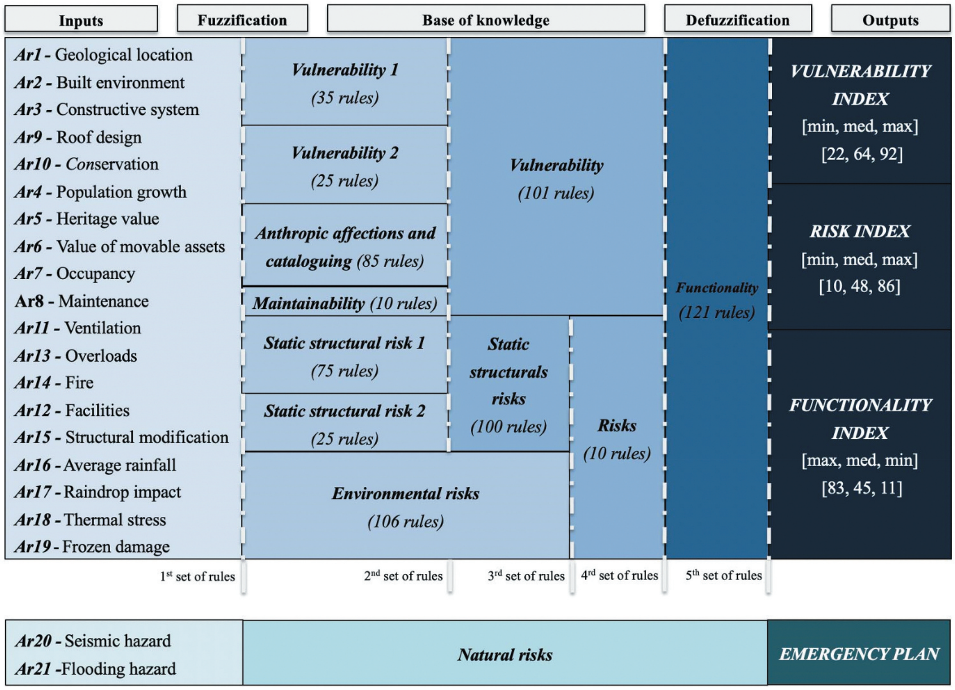

Figure 2. Hierarchical structure of the upgraded fuzzy inference system (Art-Risk 3.0), including inputs and outputs variables.

Figure 3. Location of Seville in South Europe (Spain) (left) and emplacement of *Santa Catalina* parish church in the historical city center (right).

correlation coefficient (r) of −0.938 was achieved for the 500 theoretical case studies developed and applied. The analysis of the determination coefficient (R^2) which estimates the proportion of variance of the y values (functional service life — [*FSL]* index) related to x values (risks — R index), demonstrated R^2 = 0.824, based on an exponential curve xxx, which indicates a high correlation between the variables considered in the theoretical study (functional service life and risks)Figure 6.

As stated previously, the computational model (*Art-Risk* 3.0) was defined to establish a hierarchical priority of intervention rank regarding functionality, risks and vulnerabilities of a set of heritage buildings. Following this approach, this statement was corroborated with the theoretical application of 500 hypothetical case studies, which demonstrated a strong correlation between functional service life and external risk affectionFigure 6 . However, a set of outliers is identified. In this sense, the identified outliers must be analyzed in future approaches to improve the current version of the model (Figure 6) .

Considering the validation and applicability of this fuzzy method (*Art-Risk* 3.0), the results obtained in this section have been extrapolated to a previous application of the fuzzy logic model (fuzzy building service life — *FBSL*) in 2017 (Prieto et al. 2017) where similar results were obtained. In this approach, the "y" axis shows the theoretical functional service life of heritage buildings and the "x" axis displays the

Figure 4. Sections of Santa Catalina parish church.

risks of heritage buildings. In this theoretical analysis, the risks vary between 1point (very low risk level — *R* index) to 8 points (very high risk level — *R* index) and the same occurs for the vulnerabilities, in where 1 point mean a building with very low vulnerabilities (*V* index) and 8 points mean a building with a very high vulnerability level (*V* index) (Figure 6) . The theoretical functional service life, varies between 0 (very low functional service life — [*FSL]*) and 100 (very high functional service life — [*FSL]* index) (Macias-Bernal 2010; Prieto et al. 2017). The correlation between the intrinsic vulnerability of buildings, external risk affections, and the influence of these parameters on the functional performance of heritage buildings is shown in Figure 6. As stated by Rashed and Weeks (2003), the concept of vulnerability differs from that of risk, because it is not dependent on any certain magnitude of a given event, but on the context in which the event occurs. In Figure 6, the results show that, as the values of risks increase, the building's vulnerability is no longer relevant, because against very strong risks, the functionality of the building decreases significantly, regardless of their degree of vulnerability.

The analysis presented in Figure 7 reveals that when the risks (*R*) and vulnerabilities (*V*) are very low and close to 1 point, the functional service life (*FSL*) presents a value close to 100 or even more (*FSL* tends to extend to

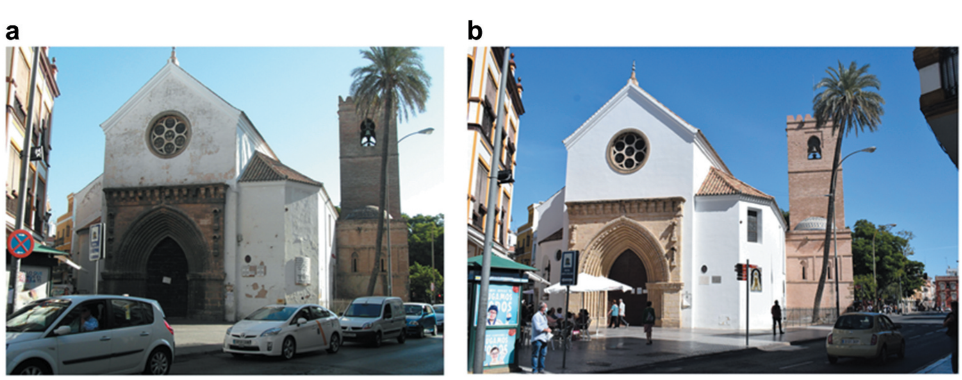

Figure 5. Church of Santa Catalina: (A) before and (B) after being restored.

infinity). Nevertheless, in cases where risks (*R*) and vulnerabilities (*V*) are very high and close to 8 points, the functional service life has a value close to 0 (*FSL* tends to be 0)(Figure 7) (). This approach stated a quantitative correlation between *FSL, V* and *R*. Therefore, a theoretical functional service life (*FSL*) index was defined, given by the following equation xxx (Macias-Bernal 2010; Macías-Bernal, Calama-Rodríguez, and Chávez-De Diego 2014):

In this section following a theoretical application of 500 case studies, confirmed that the fuzzy model (Art-Risk 3.0) presents a performance similar to the approach defined by the fuzzy model (FBSL) (Prieto et al. 2017) and the definition of the theoretical functional service life index in xxxx. This sensitivity approach helps validate the Art-Risk 3.0 fuzzy model's results, in which the highest functional service life level corresponds to the lowest vulnerability and risk affection and viceversa.

The global importance of sustainable development requires an informed decision-making process for the built environment to ensure an optimum functional service life for heritage buildings. This depends on the quantification of changes in the conditions of building materials (vulnerability and risks) over time. The creation of useful tools for the definition of preventive maintenance plans will help to increase the performance and longevity (Shohet, Puterman, and Gilboa 2002) of cultural heritage buildings.

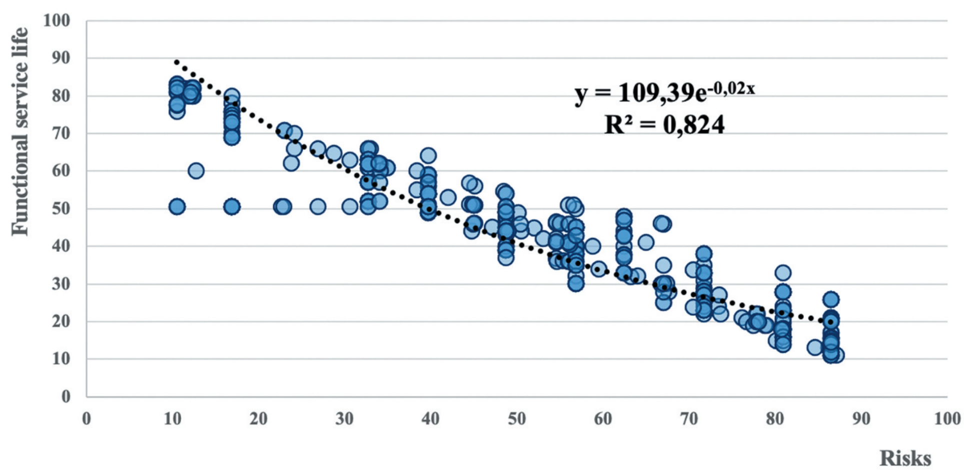

Figure 6. Functional service life and external risks affection regarding 500 theoretical case studies applied into the fuzzy logic model (Art-Risk 3.0

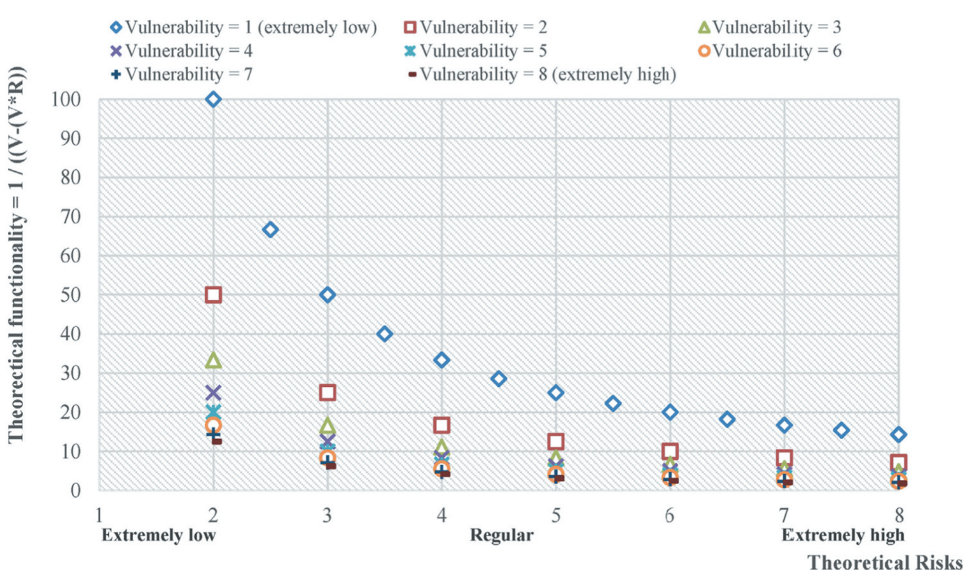

Figure 7. Relationship between functional service life and external risks affection (A. J. Prieto et al 2017.).

3.2. Use of Art-Risk 3.0 in the Santa Catalina church case study

3.2.1. Description and analysis of input variables and recorded changes

This section discusses the application of the *Art-Risk* 3.0 model to the Santa Catalina Church case study. The input variables collected are described below and the scores assigned in the technical inspections of 2012, 2019 and 2020 are compared. To facilitate their understanding, they have been classified into three large groups following the scheme of the *Art-Risk* index card: A. vulnerability; B. Static-Structural and Environmental Risk; and C. Natural Risk) (Tables 1 and 2).

The results obtained allow: (i) describing and measuring the external threats and vulnerabilities of the building in 2012, 2019, and 2020; (ii) identifying post-restoration changes; and (iii) interpreting the results obtained and defining a medium-to-long-term action protocol using the tool manual (Ortiz et al.2019).

A. Vulnerability. Variables Ar1, Ar2, Ar3, Ar4, Ar5, Ar6, Ar7, Ar8, Ar9 and Ar10 measure vulnerability.

Geological location (Ar1) assesses the suitability of construction conditions based on the existing terrain in the context. The score assigned by the software was 2: favorable, and stable. This corresponds to the value assigned to the general geotechnical map made by the Geological and Mining Institute of Spain (IGME: Geological and Mining Institute of Spain 1974). The following criteria were followed lithological, geomorphological, hydrological, and geotechnical.

Built environment (Ar2) assesses the state of the building's party walls. The Santa Catalina Church has no building, garden or grove in the immediate surroundings and corresponds to a quantitative rating of type-1 in the *Art-Risk* 3.0 model: very favorable (Figure 8)).

Construction system (Ar3) assesses the heterogeneity or homogeneity of the construction system. Santa Catalina is "a rectangular-shaped house of worship with three naves separated by quadrangular pillars, which supports pointed arches of exposed brick and a chancel covered by a ribbed vault. The central nave is covered by a cross frame with jointed rafters, forming the roof of the lateral naves. Chapels open on both sides of the lateral wall (Figure 3). This construction typology corresponds to a heterogeneous construction system without complex frameworks and receives a quantitative rating of type-3: acceptable.

Population growth (Ar4) assesses the impact of population changes on resources and abandonment of heritage structures. The Santa Catalina Church, located in the historic center of Seville, corresponds to a quantitative rating of type-2: favorable, because during the last five years, its population has grown slowly (less than 15%).

Heritage value (Ar5) assesses the degree of appreciation of the property of the community. The Santa Catalina Church is a 14th century building, with additions in the 16th and 17th centuries. It is built in the Mudejar-Gothic style and was declared a Historic-Artistic Monument in 1912. It meets the requirements of age, construction quality, historical value and recognition of protection to obtain a quantitative rating of type-1: very favorable.

Value of movable assets (Ar6) ranks the value of the movable assets existing within the property. The case study analyzed house altarpieces, sculptures, and other assets of great value due because of their liturgical and cultural appreciations. This situation corresponds to a type-1 quantitative rating: very favorable.

Occupancy (Ar7) assesses the degree of property use. In 2012, the case study analyzed had been closed and had no activity whatsoever. This situation corresponded to the type-5 quantitative rating: very unfavourable. In 2019 and 2020, post-renovation, the building was opened for weekly religious services. Given the high level of activity since, this situation corresponds to the type-2 quantitative rating: favorable.

Maintenance (Ar8) assesses the suitability of scheduled activities to preserve the structure. In the case of the Santa Catalina Church, in 2012, there were no resources available for maintenance actions, a situation that corresponds to the type-5 assessment: very unfavorable. In 2019 and 2020, although the property lacked personnel in charge for executing maintenance activities, there was a maintenance plan and activities scheduled in the medium term. This situation corresponds to the type-2 quantitative variable: favorable.

Roof design (Ar9) assesses the difficulty of evacuating rainwater from the roof. For the case study analyzed, despite the existence of joints, the roof slope allows rapid water evacuation. Thus, the quantitative rating of type-2: favorable.

Conservation (Ar10) assesses the state of conservation of façades, party walls, roofs, foundations, facilities, accessibility, and the overall structure. In the Santa Catalina Church, the 2012 inspection detected dampness in the roof and the built structure; fractures and cracks in walls; displacement; efflorescence; and cavernization processes associated with the effects of water and wind. Surface deposits and black crusts caused by urban pollutants were also detected (Figure 9) (Ortiz et al.2012; Ortiz 2014). The church interior faced a risk of collapse in the interior of the church. The damages identified correspond to the quantitative rating of type-5: very unfavorable; that is the building in a state of abandonment.

The 2019 inspection confirmed that the problems of dampness and fractures were solved and black crusts were also removed. The building was equipped with new plumbing, lighting, and fire, and intrusion detection facilities. The conservation status on this date corresponded to the type-1 quantitative rating: very favorable, optimal conservation.

The 2020 inspection identified the reappearance of cracks, small fractures, and damp spots on the exterior walls facing the north-west (Alhóndiga Street).

As shown inFigure 9, c*onservation* (Ar10) is one of the most problematic vulnerability variables. Although the interventions increased the property's resilience to maximum values in 2019, the 2020 data revel the slow reactivation of small degradation processes. In turn, the values recorded in variable Ar3 (construction system) and the problems associated with the heterogeneity of the construction system make it difficult to preserve the building and reduce its long-term functionality.

Occupancy (Ar7) and *maintenance* (Ar8) are also problematic vulnerability variables. Both decreased considerably following the intervention.

B. Static-structural and environmental risks. Variables Ar11, Ar12, Ar13, Ar14 and Ar15 quantify the static-structural hazards.

Ventilation (Ar11) ranks the building's natural cross ventilation system from most to least favorable. In 2012, the inspection recorded a completely closed building, in which the doors and windows were not regularly opened to facilitate ventilation of the building. The penetration of dampness from the subsoil and roof damage aggravated the situation. At that time, the numerical variable of type-5 was assigned: very unfavorable. In 2019, the reopening of the property and creation of a cavity wall changed the situation. For the first time, the building had cross ventilation albeit, in some of its spaces. The quantitative rating assigned was type-2: favorable. This value was maintained in 2020.

Figure 8. Cadastral mapping on PNOA orthoimage. (Ministry of transport, mobility and urban agenda, 2022)

Figure 9. a y b) fractures; c) moist area; d) erosion and black crust

Facilities (Ar12) assess whether the facilities meet the standards for the supply and sanitation of water, electricity, and fire protection equipment. The 2012 inspection showed that although the facilities did not comply with the regulations in force at the time, they were operational and, therefore, the score of type-4 was assigned: unfavorable. In 2019, following the renovation carried out, the facilities were in compliance with the standards; and therefore, the score of 1 was assigned: very favorable.

Overloads (Ar13): rank the changes in the transmission of static loads from most to least favorable. The numerical rating assigned was type-3, and the new structural overloads were acceptable.

Fire (Ar14) assesses the possibility and speed of spread of fire. The Santa Catalina Church is a stone building housing altarpieces, benches, and other wooden structures. Therefore, it is a noncombustible structure with a moderate fire load. It was assigned the score of type-2: favorable.

Structural modifications (Ar15) assessed the changes in the initial loading conditions for which the building was designed. This church exhibits numerous historical transformations and extensions. Despite the great scope of some of them, these are balanced and symmetrical modifications corresponding to the quantitative rating of type-3: acceptable.

As shown in Figure 10, the variables *ventilation* (Ar11) and *facilities* (Ar12) exhibit a higher risk level; both showed considerable interventions improvement. However, the risks associated with *overloads* and *structural modifications* (Ar13 and Ar14) remain even after the intervention, and may pose problems in the medium and long terms.

Variables Ar16, Ar17, Ar18, and Ar19 measure environmental hazards, and their values are automatically obtained using the *Art-Risk* 3.0 computer tool. These types of variables analyze the environmental context and do not allow the user to register temporary changes.

The average rainfall (Ar16) assesses the amount of rain per unit of surface area. The quantitative rating assigned was type 2: favorable, because the average rainfall ranges 600–750 mm (AEMET: State Meteorological Agency of Spain 2011).

Raindrop impact (Ar17) assesses the intensity of rain according to the Torrential Index (TI). The quantitative rating assigned was type 4: unfavorable, because the relationship between the intensity of precipitation in one hour and the mean precipitation intensity in 24 h presents values between 9 and 10 according to Standard 5.2-IC of surface drainage of highway instruction (Ministry of Public Works and Urbanism 1990).

Thermal stress (Ar18) assesses daily oscillations in temperature. The quantitative rating assigned is type 5, very unfavorable, typical of areas with daily temperature differences over 10–12°C (IGN: National Geographic Institute of Spain 2008).

Frozen damage (Ar19) assesses the daily minimum temperature. The quantitative rating assigned was type 2: favorable, because Seville has 10 to 20 days a year with minimum temperatures below 0°C (AEMET, 2015).

As shown in Figure 9, the high scores recorded for *thermal stress* (Ar18) and *raindrop impact* (Ar17) predict a high incidence of these agents of deterioration on the building in the medium and long terms.

C. Natural risk. Variables Ar20 and Ar21: seismic and flooding risks are informative variables, provided by the *Art-Risk* 3.0 computer tool. They are not used in the calculation of vulnerability, risk and functionality index using *Art-Risk* 3.0.

Seismic hazard (Ar20) assesses seismic danger according to the Seismic Resistance Construction Regulation: NCRS-02 (Ministry of Development of Spain 2009). The quantitative rating obtained was type 2, low-risk areas in Seville.

Flooding hazard (Ar21) assesses the possibility of floods based on the data provided by the National Flood Mapping System of the Ministry of Agriculture and Fisheries, Food and Environment (Ministry for the ecological transition and the demographic challenge,). The quantitative rating obtained was type 1: areas of minimum risk with a return period of more than 500 years.

In a summary,Figure 10 synthesizes the values recorded for each of the variables, before and after the intervention. Values recorded in 2019 and 2020 helps identify the immediate and medium-term results of the intervention. Currently, the most problematic variables are those associated with the presence of environmental risks: thermal stress and erosion due to torrential rain.

3.2.2. Description and analysis of the output variables

Once the variables are entered in the Art Risk 3.0 tool, the exposed fuzzy logic model offers three output values: vulnerability (value between 22.7 and 92.8), risk (value between 10.5 and 86.4) and functionality service life (value between 83.04 and 11.02). The values obtained can be compared with the interpretation tables of the model (Figure 11) to obtain recommendations for the proper conservation of the property.

As can be seen in Figure 11, the output variables provided by *Art-Risk* 3.0 register a considerable decrease in vulnerability, a slight decrease in hazard and an increase in the functionality service life of the building. If we compare the values obtained with the interpretation tables of the model Figure 12, we will obtain recommendations to ensure the correct conservation of the property.

In relation to the *vulnerability index* (VI), in 2012, it was near 72. This score corresponds to the maximum values of moderate vulnerability and is associated with buildings that exhibit conditions that should be studied in detail Figure 10 . Proximity to the high vulnerability thresholds reflects a poor state of conservation. In 2019, there was a decrease in the VI to 34. This score indicates a low degree of vulnerability and is associated with buildings that exhibit optimal conservation conditions. In 2020, although VI had risen slightly, it remained within the minimum threshold of moderate vulnerability.

Although the results obtained in 2012, 2019 and 2020 are considered moderate values, a decrease in the Risk Index (RI) was quantified between 2012 and 2019, 2020. Although these values, determined by external environmental factors, indicate the presence of threats within the context analyzed, the restoration has slightly minimize these hazards.

Finally, the *Functionality Service life Index* (FI) shows the relationship between the presence of threats, that is the RI, and the resilience of the building, measured as vulnerability (VI). The ranges obtained were moderate, but revealed a considerable increase. Although 2012 registered an FI of 37, in 2019, this had increased to 60, and in 2020, it was 56 (Figure 11). If we interpret the data obtained based on the *Art-Risk* tables, the 2012 values would be dangerously close to the maximum levels of unacceptable functionality, whereas the values obtained in 2019 and 2020 only reflect the need for periodic inspections to ensure the building's functionality.

In the Santa Catalina Church, Art-Risk 3.0 evaluates the need to plan maintenance activities and restoration interventions according to the modifications in the functionality index that the building presents over time. The 2014 restoration registered an improvement in the functionality of the building compared to the value obtained in 2012. Despite this, the 2020 revisions show a decrease in the functionality with respect to 2019 because of the deterioration in the state of conservation of the building Figure 12

In decision-making, this analysis helps prioritize risk levels and establish intervention priorities. Furthermore, the simplicity of the described method allows the inclusion of periodic reviews within maintenance policies. Its

Technical inspections carried out					2012	2019	2020
FUNCTIONALITY	VULNERABILITY	I.Constructive Vulnerability	Geological location	Ar1	2	2	2
			Built Environment	Ar2	1	1	1
			Constructive system	Ar3	3	3	3
			Roof design	Ar9	2	2	2
			Conservation	Ar10	5	1	2
		II.Antropic Vulnerability	Population growth	Ar4	2	2	2
			Heritage value	Ar5	1	1	1
			Value of movable assets	Ar6	1	1	1
			Occupancy	Ar7	5	2	2
		III.Maintainability	Maintenance	Ar8	5	2	2
	RISK	IV.Static Structural Risks	Ventilation	Ar11	5	2	2
			Facilities	Ar12	4	1	1
			Overload	Ar13	3	3	3
			Fire	Ar14	2	2	2
			Structural modification	Ar15	3	3	3
		V.Environmental Risks	Average rainfall	Ar16	2	2	2
			Raindrop impact	Ar17	4	4	4
			Thermal stress	Ar18	5	5	5
			Frozen damage	Ar19	2	2	2
		VI.Natural Risks	Seismic hazard	Ar20	2	2	2
			Flooding hazard	Ar21	1	1	1

Figure 10. Registered input variables. NOTE: Red-very unfavorable; orange-unfavorable; yellow-acceptable; light green-favorable; green-very favorable.

Church of Santa Catalina		
Output 2012		
Vulnerability Index	**Risk Index**	**Functionality Index**
71	55	37
Output 2019		
Vulnerability Index	**Risk Index**	**Functionality Index**
34	47	60
Output 2020		
Vulnerability Index	**Risk Index**	**Functionality Index**
42	47	56

Figure 11. Registered output variables Art-Risk 3.0

A.Vulnerability and risk range conditions			B.Functional service life range conditions	
Percentage	Vulnerability	Risks	Percentage	Functional description
90	Very high priority for research; short-term protection strategy is recommended	High level of risk	10	Inaceptable serviceability level, requiring immediate intervention
80			20	
70	High-medium priority for research; medium-term protection strategy is recommended	Medium level of risk	30	Building requires periodical inspections, in order to maintain acceptable serviceability level
60			40	
50	Yearly preventive surveillance and maintenance plan. Cataloguing files and vulnerability calculation must be updated in case of changes or interventions and it is advisable at least every three years of after a disaster such us floods, fires, earthquake, etc...	Acceptable level of risk	50	Building in acceptable serviceability state
40			60	
30			70	
20	No vulnerability	No risk	80	Building with an optimal serviceability conditions
10			90	

Figure 12. Interpretation tables. *Art-Risk* 3.0.

quick application makes it a useful tool not only to evaluate the necessity of intervention in a structure but also to diagnose other buildings after a disaster.

4. Conclusions

The analysis of theoretical case studies allows the validation of the Art-Risk 3.0 and its fuzzy model. In the 500 cases analyzed, the results show that if the input risk and vulnerability values increase, the output risk and vulnerability values increase and the building's functionality index decreases.

Additionally, the study conducted at the Santa Catalina Church permitted a diachronic risk analysis reflecting the states of deterioration before and after intervention, as well as demonstrating the usability of the *Art-Risk* 3.0 software.

The description of the input variables recorded in 2012 help identify the most problematic factors such as: the state of conservation, lack of occupancy and maintenance, lack of ventilation, and thermal stress. The lack of facilities requires by regulation (fire prevention, lighting, plumbing, etc.), and erosion due to rain, also hindered the building's preservation.

The changes identified between 2012 and 2019 reflect the improvements effected by the restoration activities. Problems categorized as the state of conservation, lack of occupancy and maintenance, lack of ventilation and the need to improve the facilities have already been solved. However, the input variables that continued to present problems in 2019 and 2020 reflect the active hazard. Thermal stress and erosion due to rain are factors can cause long-term problems. The heterogeneity of the building construction system, structural overloads associated with building use and structural changes must also be monitored as a preventive conservation policy.

A comparison of the output variables provided by *Art-Risk* 3.0 in 2012, 2019 and 2020, show a decrease in the levels of vulnerability and hazards and an increase in the functionality of the building. These trends represent the characteristics of a successful restorative intervention, capable of improving the resilience of the concerned property, in both the short and medium terms.

The comparison of the output obtained in Santa Catalina with the interpretation tables of the model, indicates the transition from medium-high values of hazards and vulnerability (associated with buildings where intervention is necessary) to medium-low values (associated with buildings that only require periodic maintenance). Maintaining the vulnerability and functionality of a building at a lower risk level (green), and planning maintenance restoration activities when they reach the yellow level, helps in the sustainable planning of the resources available for the conservation of the built heritage. Finally, the 500 theoretical case studies and the present real case demonstrate the usability of the *Art-Risk* 3.0 software to analyze the state of conservation of buildings in relation to its environment and facilitate the management of heritage buildings, the restoration plan and preventive conservation measure. Moreover, this proof of concept demonstrates the capability of the *Art-Risk* 3.0 software to analyze the environmental influence on the vulnerability, risk, and functional life of buildings and provides a useful tool to assess the effectiveness of these restoration treatments. Additional studies, which compare monuments in different environments and state of conservations, are in progress.

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