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An Approach Concerning Climate Change and Timber Building Resilience: Araucanía Region, South Chile

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Abstract: This study analysed climate change effects concerning the resilience of timber buildings located in southern Chile, specifically in two cities: Collipulli and Temuco (Araucanía Region). A digital fuzzy logic method was used in a set of timber buildings declared as heritage conservation buildings by Chilean Government standards. The outcomes revealed that climate change impacts did not substantially alter the functional performance of the set of heritage timber buildings examined. This study's results can assist in developing upcoming strategies or recommendations that can support adaptation policies for administering architectural heritage regarding climate change forecasts. These data will invaluably help stakeholders who support the conservation of timber structures located in the southern environment of Chile and under the changing climatic hazard.

Keywords: heritage buildings; resilience; climate change; Chile; functional performance

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1. Introduction

Heritage buildings and infrastructures are one of the most visible parts of a society and even of a region's history, showing several forms of cultural values expressed over time [1]. Due to the fact of their cultural, architectural and, often, their social value, these kinds of structures should be preserved, and the system of values, practices and symbols of identity that allow for the preservation of their particular context should be maintained [2,3].

International and even national entities recognise the crucial need to create several innovative and sustainable tools to support balanced planning regarding the built environment [4]. Recently, several researchers have noted the importance and direct contribution of cultural heritage to more sustainable development in specific local contexts [5]. Mainly due to the fact of their cultural and social value, architectural inheritance should be conserved, preserving the practices and symbols of a specific national, regional and local identity over time [2]. Hence, the NOAH European project established an innovative mechanism for managing and transmitting vital information regarding floods, which mainly focused on the Rhine River, and its possible influence on predicting flooding [6]. The Climate for Culture project is related to global climate change, and it investigates the potential impact of climate change on Europe's cultural heritage assets, especially on historic buildings and their interiors [7]. Likewise, the Art-Risk project developed a computerised tool for the preventive conservation of heritage in urban centres based on artificial intelligence models and focused on the particular context of Europe [8]. Thus, currently, there is a significant necessity to improve new and coherent policies focusing on the management, preservation and protection of the built heritage environment considering new possible scenarios of external environmental hazards such as the effects of climate change. Hence, institutions, authorities and stakeholders have accepted the inevitable requirement to maintain their socio-cultural resources [9]. This is paramount because the renovation of urban heritage city centres offers several benefits related to several variables associated with regenerating neighbourhoods [10], which could be more appropriate for possible new external investments.

Therefore, the Chilean government, specifically the Ministry of Housing and Urbanism, promotes phased programmes for safeguarding the city's heritage areas [11]. The urban heritage city centre is mainly constituted of public spaces, called historical zone conservations (HZCs), and buildings, called historical building conservations (HBCs), which, due to the fact of their historical features, are defined as examples of collective memory conveyed from generation to generation. These urban and architectural locations reflect several cultural features that define the community backgrounds of the municipality and even the territory in which they are placed [11]. Urban heritage protection policies aim to revitalise Chilean municipalities [11], creating a better-looking environment for inhabitants through urban planning that preserves the uniqueness of regions [3,12], stimulating urban heritage protection and preserving these buildings in satisfactory performance conditions.

Regarding international organisations, the International Council on Monuments and Sites (ICOMOS) [12] specified that the effects of climate change and global warming are among the key pressures for current societies and their direct historical environments. Similarly, the Intergovernmental Panel on Climate Change (IPCC) was generated to deliver an evaluation of the economic, social, environmental, technical and scientific situations related to the origins of climate change and its consequences [13]. The effects of climate change, specifically extreme weather events, have been found to accelerate the current degradation of heritage buildings and, consequently, these kinds of events can reduce the physical and functional performances of these constructions [14].

In 2017, Fatoric and Seekamp [15] found that research concentrated on heritage and resources at risk due to the fact of climate events arose at the beginning of the 21st century. Notably, these kinds of studies have increased over the last several years. Although various research methodologies have been used, new additional studies are required to understand the possible future impacts of climate change [16] on the deterioration phenomenon of heritage structures. Specifically, novel research should be devoted to safeguarding cultural heritage by adopting policies to address upcoming climatic actions [17]. Heritage structures must be safeguarded, and medium- and long-term conservation programmes should be designed and implemented through monitoring the performance of conservation actions [18,19].

Northern Europe, Asia, and North America are the international regions in which most of the research related to climate change effects have been conducted on architecture, construction and engineering; however, in the Southern Hemisphere, especially in South America, studies focusing on this specific issue are absent. Thus, new research must be developed to assess and understand climate change effects on the architecture, construction and engineering sectors, particularly for heritage buildings, to achieve new advances to be adopted in future practices.

2. Research Objective

The main novelty of this approach relies on evaluating timber buildings in Chile and quantifying possible future climate change effects. The results obtained can improve the understanding of climate change effects on timber buildings in southern Chile, especially in the Araucanía Region. Furthermore, the proposed system can be adjusted to aid in the establishment of innovative adaptation measures and mitigation approaches to propose possible upcoming maintenance programmes for timber buildings in other cities or regions of the continent. The motivation for this analysis was based on the demand to develop a public management plan focusing on safeguarding regional heritage buildings emplaced in South America and based on Chilean regulations. The outcomes reached can be advantageous to different users, owners or sponsors sensible for the maintainability of heritage structures, because they can reduce the possibility of buildings' degradation and stimulating urban renewal in the southern context of Chile.

3. Materials

3.1. Characterisation of the Buildings Analysed

In this analysis, two cities located in the region of La Araucanía (southern Chile) were analysed. Figure 1 shows the geographic locations of cities in South America.

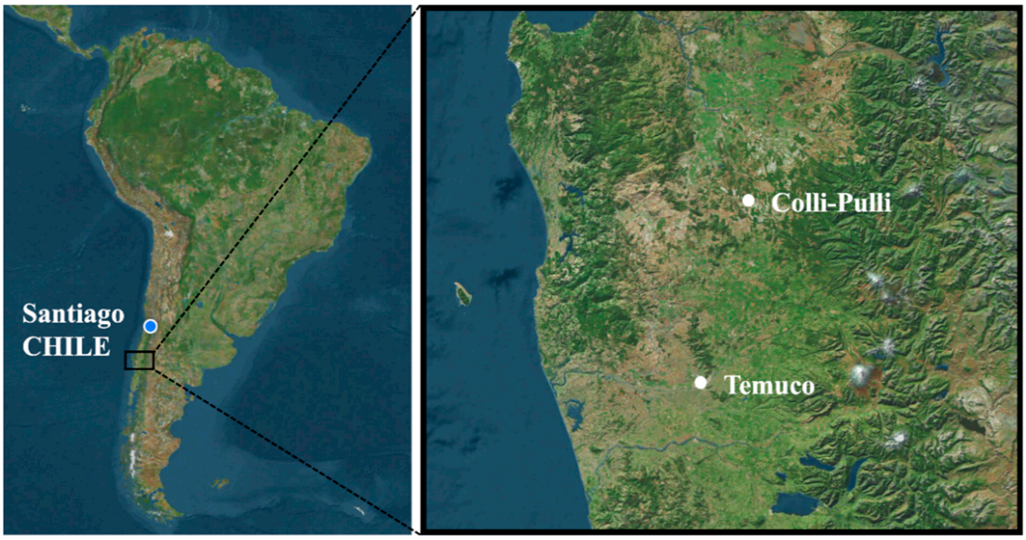

Figure 1. Location of the two municipalities under analysis (Araucanía Region) in southern Chile.

The city of Temuco was founded in 1881 as a Fuerte Recabarren camp. As a city, Temuco resulted from the so-called pacification of La Araucanía. Currently, this city is the capital of the La Araucanía Region [20]. The geographical location of Temuco (elevation 360 m) relates to the latitude 38.74 °S and the longitude 72.59 °W. The case studies were emplaced approximately 680 km to the south of Santiago (capital) (Figure 1). Temuco is located on the banks of the Cautín River. The national census conducted in 2017, by the National Statistics Institute of Chile, established the population of Temuco to be approximately 221,000 inhabitants.

Collipulli is a commune placed in the province of Malleco in the Araucanía Region. The city is located close to the Central–South railway. It was founded in 1867 during the Occupation of Araucanía [20]. The current population is approximately 23,300 inhabitants. The geographical location of Collipulli (elevation 244 m) corresponds to the latitude 37.96 °S and the longitude 72.44 °W. The distance from Santiago is nearly 581 km to the south (Figure 1).

3.2. Climatic Environmental Characterisation

Regarding Köppen–Geiger climate cataloguing, both cities are characterised by Mediterranean weather with hot summer seasons [21]. Because there is no operational weather station near Collipulli, climate information from the Centre for Climate and Resilience Research (CCRR) was used [22]. This centre has developed a platform to visualise data from climate models [22]. This platform provides information on various meteorological parameters including the mean annual temperature and the annual amount of rainfall for the whole of Chile for historical periods (1985–2005) and future periods (2020–2044 and 2045–2069). For future periods, data are provided for two future climate change scenarios: RCP2.6 (the most positive scenario) and RCP8.5 (the most negative scenario).

A detailed description of these climate change scenarios is presented in an IPCC document (IPCC, 2013). Likewise, in previous research by Prieto et al. (2020) and Verichev et al. (2020), several examples of the use of these scenarios can be found in climate research in the fields of civil engineering and architecture [23,24].

Concerning the determination of the annual mean values of the climatic parameters, the mean value of the ensemble of climatic models was used. For the reconstruction of the climate data for the historical period, the average value of an ensemble of 57 climate models of different spatial resolutions presented on the CCRR platform [22] was used. For the RCP2.6 scenario, data from 28 climate models were considered, and for the RCP8.5 scenario, 44 models [22] were considered.

The quality of the climate models was evaluated based on their ability to reproduce the climate for a historical period. The CCRR platform provides annual or monthly average climate data already calculated and analysed. Concurrently, this platform implements the interpolation of data from the nodes of the climate models to any geographical point.

Table 1 shows that the mean error in the definition of the annual temperature for the historical period at both geographical points of this study was −0.01 °C for the mean of the ensemble of the climatic models. The climate models, on average, reproduced precipitation with a 99.91% level of precision in Temuco and 99.88% in Collipulli for 1985–2005.

Table 1. Data regarding the average annual precipitation and temperature for the three climatic periods for the two locations (i.e., Temuco and Collipulli).

Temperature (°C)	**1985–2005**	**2020–2045**		**2045–2069**	
		RCP2.6	**RCP8.5**	**RCP2.6**	**RCP8.5**
Temuco	11.1(−0.01 ± 0.01)	11.7(± 0.08)	12.0(± 0.06)	11.8(± 0.10)	12.8(± 0.10)
Collipulli	11.4(−0.01 ± 0.01)	12.1(± 0.07)	12.3(± 0.06)	12.2(± 0.10)	13.2(± 0.11)
Precipitation (mm)	**1985–2005**	**2020–2045**		**2045–2069**	
		RCP2.6	**RCP8.5**	**RCP2.6**	**RCP8.5**
Temuco	1450(99.91% ± 0.32%)	1369(± 31)	1369(± 28)	1348(± 31)	1279(± 32)
Collipulli	1356(99.88% ± 0.36%)	1271(± 32)	1279(± 29)	1254(± 32)	1195(± 37)

In Table 1, for the RCP 2.6 scenario, the temperature increase will slow down after the 2020–2045 period. Concurrently, the increase in the mean annual temperature value will be 1.7 °C and 1.8 °C for the period 2045–2069 for the RCP8.5 scenario compared to the historical period, respectively, for Temuco and Collipulli.

In Temuco, the annual rainfall is expected to decrease by 5.6% in 2020–2045 compared to the historical period for the two scenarios. In 2045–2069, the expected decrease in precipitation will already amount to 7% and 11.8%, respectively, for RCP2.6 and RCP8.5. For Collipulli, from 2020–2045, the decrease in rainfall will be 6.3% and 5.7%, respectively, for RCP2.6 and RCP8.5. In 2045–2069, the predicted decrease in precipitation will reach 7.5% and 11.9%, respectively, for RCP2.6 and RCP8.5.

Of course, due to the geographical proximity of these cities, both the absolute values of the climatic parameters and the trends in the future changes of these parameters are quite similar. The information was also used to analyse the effects of climate changes on the performance of the timber buildings examined.

3.3. Characterisation of the Sample

The sample under analysis is categorised as an HBC regarding the main regulations of the Communal Regulatory Plan (CRP) [11]. The total sample comprised 14 heritage structures emplaced in the Araucanía Region, which were erected between the 19th and 20th centuries. However, seven buildings were particularly selected due to the fact of their similarities and presentation of some homogeneity related to their timber structures. Thus, the seven case studies were selected due to the study's focus on wooden buildings, and a homogeneous sample was considered to minimise dispersion in the subsequent analysis of the model results.

The constructive systems implemented by Europeans, mainly Germans, in the southern regions of Chile, reproduce some of the principal features of their former homeland, although there are variations due to the use of wood as the main material in the local region. It is one of the primary accessible materials for production in this region [25,26].

Concerning several characteristics of the buildings, the ground floor is organised, in practically all of the case studies, around an axial axis formed by a central corridor or a corridor under the category of a hall [27]. The volume presents a glazed gallery, normally turned towards the north to leverage solar radiation. The case studies have listed turrets, bow-windows and projecting windows, galleries, corridors and accesses of imperial scales as characteristics [28]. The ceilings are rarely used, unlike what is appreciated in the areas farther south [29].

These houses are preferably built as wood houses; however, towards the beginning of the 20th century, stucco brick masonry was incorporated, especially in baseboards or certain areas of the house [29]. There is also the use of an adobillo, a partition constructed using pieces of wood with a square section and a large square, usually oak, that is filled with adobe and then covered with cement mortar or metal plates [30]. A variant of this construction system is the "English partition" in which the adobe is replaced by unplanted clay brick, thus giving the appearance of a brick wall with its structures, sills and diagonals in sight [28,29]. Figure 2 shows the main characteristics of the case studies examined.

Figure 2. Samples under analysis.

4. Fuzzy Logic Methodology for Evaluating Heritage Buildings' Functional Performance

The system implemented in this study was based on fuzzy set theory, which was founded in 1965 by Lofti A. Zadeh (1965) [31]. Fuzzy sets are commonly used as a support system for decision-making and engineering procedures [32], particularly in cases where the phenomenon under examination presents different levels of uncertainty associated with its nature [33]. This happens in evaluating the functional performance of structures and the external hazards caused by different parameters such as social, natural or environmental transformations. In 2014, Macias-Bernal et al. (2014) [34] proposed an early version of the system: fuzzy building service life (FBSL). This method can be used to establish priorities for interventions in heritage constructions under similar constructive characteristics and was established based on the ISO 31000 risk management standard [35,36]. This fuzzy logic system has been correlated and validated to another predictive model that evaluates the physical service life or degradation of building components. The results revealed that when the degradation of building components increase, their functionality index decreases. To perform this analysis, the degradation conditions of 647 claddings (84 rendered facades, 177 painted surfaces, 183 ceramic claddings and 203 natural stone claddings) emplaced in southwestern Europe (central and south Portugal) were analysed. A strong relationship between the two indexes considered was obtained (with a determination coefficient of

0.673 for rendered facades, 0.833 for painted surfaces, 0.764 for ceramic claddings, and 0.756 for natural stone claddings), showing an inverse correlation between them [37].

This fuzzy inference system can provide the overall functional performance of buildings regarding five variables (v_1–v_5) related to intrinsic vulnerabilities (Table 2) and 12 variables related to external hazards (r_6–r_{17}), which are specified in Table 3. In Table 4, a correlation between average annual precipitation (mm), average annual temperature (°C), and the input variables, r_{12} (rainfall) and r_{13} (temperature), is provided based on previous approaches and on the local geographical context of the Araucanía Region [3,38]. From Table 4, two variables—annual precipitation and average annual temperature—are directly related to climate. Using the data detailed in Table 1, first, the overall functional performance of buildings under study in climatic conditions for the period 1985–2005 was established. Further, the set of buildings was remodelled based on two main hypotheses: (i) all input variables of the constructions were unchanged concerning the previous stage because it was not possible to recover enough information to predict the remaining variables' evolution in the future [39]; (ii) only the atmospheric hazards (r_{12}—rainfall; r_{13}—temperature) were re-analysed in a new scenario of climate change using the information presented in Tables 1 and 4.

The fuzzy system was executed through *Xfuzzy* 3.0, which is open-access software developed by the Microelectronics National Centre of Spain [40,41].

Table 2. Input variable descriptions related to buildings' vulnerabilities [36].

Vulnerabilities	Ids	Quantitative and Qualitative Evaluation	Qualitative Description
Geological location	v_1	1.0—favourable	Optimal stability ground conditions
		2.5—medium	Satisfactory stability ground conditions
		4.0—unfavourable	Critical stability ground conditions
Roof design	v_2	1.0—favourable	Very fast water evacuation of the roof
		4.5—medium/regular	Normal water evacuation of the roof
		8.0—unfavourable	Very slow water evacuation of the roof
Environmental conditions	v_3	1.0—favourable	Building without a complex construction around it
		4.5—medium/regular	Intermediary valuation concerning favourable and unfavourable states
		8.0—unfavourable	Structure emplaced inside of complex constructions (city centres)
Constructive system	v_4	1.0—favourable	Uniform constructive system features
		4.5—medium/regular	Constructive system is defined between uniform and completely heterogeneous constructive system features
		8.0—unfavourable	Constructive system presents several heterogeneous features
Preservation	v_5	1.0—favourable	Optimal state
		4.5—medium/regular	Normal preservation state
		8.0—unfavourable	Neglected preservation state

Table 3. Input variables descriptions related to external hazards [36].

External Hazards	Ids	Quantitative and Qualitative Evaluation	Qualitative Description
Static–Structural			
Load state modification	r_6	1.0—favourable	Slight load state modifications (low hazard)
		4.5—medium/regular	Symmetric and balanced load state modifications (medium hazard)
		8.0—unfavourable	Disorderly load state modifications (high hazard)
Live loads	r_7	1.0—favourable	Live load below the original condition (low hazard)
		4.5—medium/regular	Live load equal to the original condition (medium hazard)
		8.0—unfavourable	Live load exceeding the original condition (high hazard)

Table 3. *Cont.*

External Hazards	Ids	Quantitative and Qualitative Evaluation	Qualitative Description
Ventilation	r_8	1.0—favourable	Natural cross-ventilation in all areas examined (low hazard)
		4.5—medium/regular	Natural cross-ventilation in just some areas examined (medium hazard)
		8.0—unfavourable	No natural cross-ventilation (high hazard)
Facilities	r_9	1.0—favourable	All facilities are in use (low hazard)
		4.5—medium/regular	Some facilities are in use, or they are not ready to be used (medium hazard)
		8.0—unfavourable	The facilities are not possible to be used (high hazard)
Fire	r_{10}	1.0—favourable	Low fire load regarding a combustible structure (low hazard)
		4.5—medium/regular	Medium fire load regarding a combustible structure (medium hazard)
		8.0—unfavourable	High fire load regarding a combustible structure (high hazard)
Inner environment	r_{11}	1.0—favourable	Maximum level of health, cleanliness and hygiene of the building's spaces (low hazard)
		4.5—medium/regular	Medium level of health, cleanliness and hygiene of the building's spaces (medium hazard)
		8.0—unfavourable	Low level of health, cleanliness and hygiene of the building's spaces (high hazard)
Atmospheric			
Precipitations	r_{12}	1.0—favourable	Low annual precipitations
		4.5—medium/regular	Medium annual precipitations
		8.0—unfavourable	Maximum annual precipitations
Temperature	r_{13}	1.0—favourable	Low temperature variances
		4.5—medium/regular	Medium temperature variances
		8.0—unfavourable	Maximum temperature variances
Anthropic			
Population growth	r_{14}	1.0—favourable	Population increases of more than 15%
		4.5—medium/regular	No population increase
		8.0—unfavourable	Population increases of less than 5%
Heritage value	r_{15}	1.0—favourable	High historical value
		4.5—medium/regular	Normal historical value
		8.0—unfavourable	Low historical value
Furniture value	r_{16}	1.0—favourable	High social, cultural and liturgical value
		4.5—medium/regular	Medium social, cultural and liturgical value
		8.0—unfavourable	Low social, cultural and liturgical value
Occupancy	r_{17}	1.0—favourable	High occupancy level
		4.5—medium/regular	Medium occupancy level
		8.0—unfavourable	Low occupancy level

Table 4. Relationship between average annual precipitation, average annual temperature, and valuation of the atmospheric input parameters (r_{12}—rainfall; r_{13}—temperature) [39].

r_{12}—Rainfall/r_{13}—Temperature	Average Annual Precipitation (mm)	Average Annual Temperature (°C)
1.0	<100	>18.0
1.5	100–200	18.0–17.0
2.0	200–300	17.0–16.0
2.5	300–350	16.0–15.0
3.0	350–400	15.0–14.0
3.5	400–450	14.0–13.0
4.0	450–500	13.0–12.0
4.5	500–750	12.0–11.0
5.0	750–1000	11.0–10.0

Table 4. *Cont.*

r_{12}—Rainfall/r_{13}—Temperature	Average Annual Precipitation (mm)	Average Annual Temperature (°C)
5.5	1000–1500	10.0–9.0
6.0	1500–2000	9.0–8.0
6.5	2000–2500	8.0–7.0
7.0	2500–3000	7.0–6.0
7.5	3000–5000	6.0–5.0
8.0	>5000	<5.0

4.1. Fuzzification Phase

This process concerns the transformation of crisp parameters into different ratings of diffuse membership functions [42]. The methodology mainly concerns Gaussian-type membership functions as one of the most suitable functions for modelling the functionality of timber structures, except for the geological location parameter that implements four trapezoidal membership functions (concerning four types of terrain). Gaussian-type membership functions offer good accuracy regarding small mean square error [43]. The set of input parameters was fuzzified in particular membership functions, μ_A, in which the universe of discourse is represented by U. A fuzzy set reaches any value described in the range [0,1] [44].

A membership function, μ, assigns to every component a degree of membership in fuzzy set A, going from zero to one [45] (Equation (1)).

$$\mu_A : U \to [0,1] \quad (1)$$

The fuzzy logic model considers the operator "and" as a connector that is described as an intersection. Therefore, given two sets, A and B, defined by their individual U, the intersection of both sets is $A\hat{}B$, and its membership function is defined in Equations (2) and (3) [46]:

$$\mu_A \wedge \mu_B (x,y) = T[\mu_A(x),\ \mu_A(y)] \quad (2)$$

$$T(x,y) = \min(x,y), \quad (3)$$

where $T(x,y)$ = *T-norm* [47], which conforms with the commutative, associativity and monotony properties as seen in Equation (3). The fuzzy inference system ($FBSL_{2.0}$) uses the minimum as a connective [48].

4.2. Knowledge Base and Inference Rules

A set of professional experts in structures and building management (specialists concerned with the restoration and pathology of heritage structures) was consulted during the model's design phase [34,49]. The expert survey established 354 diffuse inference rules. An application based on the Delphi method was used to treat each expert's answer [50]. The base of knowledge was a set of fuzzy rule controls, including linguistic labels, describing the knowledge of professional experts of the controlled method. Mamdani's fuzzy model, one of the most accepted procedures and algorithms, was used in this approach [51]. Normally, the premise of the inference rule is established as combinations of input membership functions—*IF*, and the consequence part of the rule is stated as the output membership functions—*THEN*. In Table 5, a set of 10 *IF–THEN* inference rules are described. The theoretical inference rules are defined as follows in Equation (4):

$$\begin{matrix} Rule\ (v_1) = w_1\ is\ p_1\ AND\ x_1\ is\ q_1\ AND\ y_1\ is\ r_1 \ldots THEN\ z_1\ is\ s_1 \\ Rule\ (v_n) = w_n\ is\ p_n\ AND\ x_n\ is\ q_n\ AND\ y_n\ is\ r_n \ldots THEN\ z_n\ is\ s_n \end{matrix} \quad (4)$$

where p_1, q_1, r_1, s_1, p_n, q_n, r_n and s_n denote the linguistic values characterised by fuzzy sets.

Table 5. *IF–THEN* fuzzy inference procedures and rules generated by professionals' knowledge.

ID Inference Rules	*IF*	Premise One	*AND*	Premise Two	*THEN*	Possible Consequences
1	*IF*	Geological location is optimal	*AND*	Constructive system is homogeneous regarding the materials used	*THEN*	Vulnerability of the buildings should be very low
2	*IF*	Geological location is extremely poor	*AND*	Environmental conditions are regular	*THEN*	Vulnerability of the buildings is very aggressive concerning a normal state of building conservation
3	*IF*	Occupancy is very high	*AND*	Heritage value is very high	*THEN*	Anthropic risks are very high
4	*IF*	Roof is in a neglected state	*AND*	Preservation is poor	*THEN*	Vulnerability is very high
5	*IF*	Ventilation does not exist inside the building	*AND*	Inner environment is normal	*THEN*	Static–structural risks should be normal
6	*IF*	The building presents several load state modifications over its service life	*AND*	Facilities do not follow the current standards	*THEN*	Static–structural risks will be emplaced in an aggressive situation to the current state of the building
7	*IF*	Rainfall and wind normally are not very high	*AND*	There are no significant variations between minimum and maximum temperatures	*THEN*	Atmospheric risks are not aggressive to the building
8	*IF*	The building has been intervened with only several months ago	*AND*	Occupancy is normal concerning the building's dimensions	*THEN*	The building does not present a high vulnerability
9	*IF*	Anthropic risks are very low	*AND*	Vulnerability is at an acceptable level	*THEN*	The durability of the building is very good
10	*IF*	Atmospheric risks are very aggressive to the current state of the building	*AND*	Static–structural risks present a high affection	*THEN*	The durability of the building decreases

4.3. Defuzzification Phase

The defuzzification phase obtains crisp values representing the fuzzy information generated by the fuzzy inference system. The centre of the area (CoA), one of the most successful defuzzification processes, was used [52,53]. Equation (5) presents the mathematical defuzzification expression for estimating the functional performance index of buildings:

$$FSBL_{2.0} = \frac{\sum_i y_i \cdot \mu_B\,(y_i)}{\sum_i \mu_B\,(y_i)} \quad (5)$$

This method addressed a semi-qualitative output founded on the evaluation of the specialists for every structure considered. The output's levels of performance (Conditions A, B and C) of the fuzzy expert system are defined in Table 6.

Table 6. Functional performance states in the context of southern Chile (Araucanía Region).

ID Conditions	Range	Levels	Description
A	(51–30)	Upper level (Green colour)	Vulnerabilities and external hazards are considered low. Therefore, a preventive safeguarding action is not specifically needed in the near future.
B	(30–20)	Middle level (Orange colour)	Vulnerabilities and external hazards are observed to be moderate. Thus, the costs and benefits need to be balanced when deciding when it is necessary to intervene.
C	(20–09)	Lower level (Red colour)	Vulnerabilities and external hazards are considered particularly aggressive to the building. Therefore, inspection and preventive maintenance action should be immediately recommended.

5. Results and Discussion

The next three subsections discuss the applicability of the fuzzy logic model to the set of case studies examined in the Araucanía Region (southern Chile): (i) application regarding current climate conditions; (ii) application considering two climatic situations (RCP2.6 and RCP8.5) of climate change predictions for a near future period (2020–2044); (iii) application of the fuzzy logic system to the sample concerning two specific climatic situations (RCP2.6 and RCP8.5) for a distant future period (2045–2069).

5.1. Fuzzy Logic System Applied to Heritage Timber Structures Regarding Current Climatic Conditions

Regarding the $FBSL_{2.0}$ system's application for southern Chile, a previous sensitivity analysis was performed to reach the maximum and minimum probable values of the model improved by Prieto et al. (2020) [38]. These prior examinations confirmed that the lowest output of the fuzzy logic system (9 points) achieved was also obtained in European contexts for Spain and Portugal [54]. Similarly, the maximum possible value for the functional performance output was established as 51 for buildings in southern Chile (Table 5). The fuzzy model maintained a constant total of three input variables encompassing the emplacement and the climatic present and future scenarios of the timber buildings analysed: geological location (v_1), rainfall and wind (r_{12}) and temperature (r_{13}).

In this research, the functional performance method ($FBSL_{2.0}$) was applied to a total of seven timber buildings located in southern Chile: four in the capital region of Temuco and three in the city of Collipulli. Concerning their administrative location, 100% of the cases were in the Araucanía Region and followed the set of HBC timber buildings as defined by the CRP [11]. Considering the applicability of the model, Table 7 specifies the data concerning the input variable valuation and the functionality (output parameter) of the cases analysed. In this analysis, a case study (14.3% of the sample) reached the lowest valuation (Condition C) regarding its functional service life, meaning that external risks and vulnerabilities were observed as especially aggressive to the building or structures analysed. Therefore, inspection and preventive maintenance action should be immediately recommended. A total of four case studies (57.1% of the sample) were classified as Condition B (orange colour) in which vulnerabilities and risks were considered moderate, where the benefits and costs were balanced in order to decide when it would be crucial to intervene. Finally, 28.6% of the samples (two buildings) were ranked as Condition A in which the risks and vulnerabilities were perceived as low; thus, intervention is not required in the near future (Table 8). Regarding a particular analysis of the sample and functionality conditions, the following results were obtained: (i) regarding Condition A, the case studies COL-01 and COL-03 in Collipulli were classified in this situation; (ii) most of the samples were classified as Condition B. In Collipulli, two cases (28.6%) were ranked as having the functional performance of Condition B (COL-04 and COL-02). Temuco also presented two cases (TEM-02 and TEM-03) in Condition B (28.6%). Finally, a case located in Temuco (TEM-01) was classified as Condition C (Table 7).

Table 7. Input variables and functional performances (outputs) for seven timber structures examined in the Araucanía Region, southern Chile (climatic period 1985–2005).

Ids	Location	Vulnerability					Hazards												Output	
								Static-Structural					Atmospheric		Anthropic					
		v_1	v_2	v_3	v_4	v_5	r_6	r_7	r_8	r_9	r_{10}	r_{11}	r_{12}	r_{13}	r_{14}	r_{15}	r_{16}	r_{17}	$FBSL_{2.0}$	Functionality Conditions
TEM-01	Temuco	4.0	3.5	5.0	2.5	5.5	2.5	3.0	5.0	3.0	6.0	5.0	5.5	4.5	4.0	1.0	5.5	5.0	19.58	C
COL-04	Collipulli	4.0	4.0	2.5	2.3	4.0	4.0	5.0	5.0	2.4	5.0	5.0	5.5	4.5	4.0	1.0	3.0	2.5	24.11	B
COL-02	Collipulli	4.0	2.0	5.0	3.0	4.8	3.0	2.0	5.0	4.0	5.0	5.0	5.5	4.5	4.0	1.0	5.5	5.0	24.16	B
TEM-02	Temuco	4.0	3.0	7.0	2.0	5.0	3.0	2.5	4.0	2.5	4.5	5.0	5.5	4.5	4.0	1.0	4.5	2.0	27.87	B
TEM-03	Temuco	4.0	4.5	6.0	3.0	3.5	2.5	2.5	4.0	2.5	4.5	5.0	5.5	4.5	4.0	1.0	4.5	2.0	29.53	B
COL-03	Collipulli	4.0	4.0	3.5	3.0	4.0	2.0	3.5	4.5	3.0	5.0	5.0	5.5	4.5	4.0	1.0	3.0	2.5	30.92	A
COL-01	Collipulli	4.0	4.0	4.2	2.0	2.0	2.0	2.0	4.5	2.0	5.0	5.0	5.5	4.5	4.0	1.0	3.0	4.0	35.40	A

Table 8. Functional performance of the seven timber structures in the cities of Temuco and Collipulli before and after climatic variations (RCP8.5) for 2045–2069.

Ids	Functionality				Functionality				
	1985–2005 (According to Table 7)				2044–2069				
	r_{12}	r_{13}	$FBSL_{2.0}$	Condition	r_{12}	r_{13}	$FBSL_{2.0}$	Condition	Delta $FBSL_{2.0}$
TEM-01	5.5	4.5	19.58	C	5.5	4.0	19.52	C	−0.06
COL-04	5.5	4.5	24.11	B	5.5	3.5	22.67	B	−1.44
COL-02	5.5	4.5	24.16	B	5.5	3.5	25.67	B	1.51
TEM-02	5.5	4.5	27.87	B	5.5	4.0	27.44	B	−0.43
TEM-03	5.5	4.5	29.53	B	5.5	4.0	29.06	B	−0.47
COL-03	5.5	4.5	30.92	A	5.5	3.5	30.35	A	−0.57
COL-01	5.5	4.5	35.40	A	5.5	3.5	34.42	A	−0.98

5.2. Climate Change and Building Performance for a Near Future Period (2020–2044)

Based on an introductory analysis of climate change conditions in the near future, minor differences between the current climatic conditions and the predicted period of 2020–2044 (Table 1) were observed. The reduction in annual precipitation and the increase in temperature in both locations (Table 1), Collipulli and Temuco, parallel the previous research analysed [55], demonstrating a decrease in precipitation for Central and South America, which will not generally induce an extreme further deterioration of the HBCs examined (Table 8). Thus, fewer actions related to precipitation with medium- or low-intensity risks should occur [56].

Evolved from the predictive information obtained from the CCRR (2019) for the near future (2020–2045), the average annual precipitation will decrease between 77 and 85 mm for both locations (Temuco and Collipulli) for RCP2.6 and the pessimistic scenario RCP8.5. Considering temperature (°C), Temuco and Collipulli showed a maximum increase in average annual temperature for the pessimistic scenario (RCP8.5), which will be around 0.9 °C; however, when analysing the optimistic scenario (RCP2.6), Temuco presented the lowest increase in average annual temperature (0.6 °C). For Collipulli, the increase in the average annual temperature was 0.7 °C. This analysis confirmed a decrease in the annual average precipitation predicted and an increase in the annual average temperature predicted regarding the regional zone (Table 1).

Based on the results achieved, no several variations among the current situation and the predicted climatic situations of 2020–2044 (Table 1) were identified. The fuzzy logic system was not sensitive enough to the very slight deviations in climatic conditions for 2020–2044. The functional performance predictions for the sample concerning RCP2.6 (i.e., the optimistic scenario) and RCP8.5 (i.e., the pessimistic scenario) for the period from 2020–2044 remained practically the same. This was mainly due to the fact of climate change, as the patterns of its impacts on buildings are particularly difficult to recognise because these changes occur at a very slow pace and, normally, changes in the near future are challenging to perceive [57].

5.3. Climate Change and Building Performance for a Distant Period (2044–2069)

Considering the prediction information gained from the CCRR (2019) regarding the period between 2044 and 2069, the average temperature (annual measure) will have a minimum increase of 0.7 °C from the current weather data (1985–2005) concerning the most optimistic predictions (RCP2.6) and an extreme increase of 1.8 °C for the pessimistic scenario (RCP8.5) (Table 1). This growth in average temperature (annual measure) was consistent in the cities examined. Considering the precipitation variable, Temuco and Collipulli presented the same decrease in annual average precipitation (−102 mm) for the optimistic prediction (RCP2.6) from 2044 to 2069. For the RCP8.5 scenario, in this period, Temuco showed the greatest reduction (171 mm) in annual average precipitation, which was less than the current weather data registered, followed by Collipulli, with a decrease of approximately 161 mm in annual average precipitation (Table 1).

Thus, the decrease in rainfall and the increase in temperature were consistent for the cities analysed in southern Chile. It has been determined that climatic prediction models normally minimise the average rainfall during the austral summer season over the Patagonia Region and in the southern regions of the Andes mountains but increase precipitation quantities near Peru. Vera et al. (2006) [58] remarked that one of the most substantial features that characterises wintertime precipitation in the Austral areas of South America is the clear decrease in annual precipitation levels over almost the entire region.

The precipitations (r_{12}) and temperature (r_{13}) input parameters were adjusted for the case studies of Temuco and Collipulli. In previous studies, atmospheric inputs were connected with real data gained from average precipitations (mm) and average temperatures (°C) in Chile [39]. The current version of the fuzzy system cannot contemplate unpredictable, severe climatic incidents.

Regarding the optimistic (RCP2.6) and pessimistic (RCP8.5) scenarios for 2044–2069, only the atmospheric variables (r_{12} and r_{13}) were revised. This situation was considered to identify the specific pattern of future degradation related to the buildings' functionality. Regarding the remaining 15 variables, they were assigned based on the in-situ survey and the preservation of their previous climatic scenarios analysed.

The current version of the $FBSL_{2.0}$ system cannot identify differences in the functional performances for the case studies examined regarding the most optimistic scenario RCP2.6 for 2044–2069 (distant future); however, considering the most pessimistic scenario RCP8.5 (2044–2069), the method could show deviations in the functional performances of timber structures before and after climatic circumstances. The connections between the variables were as follows:

- Collipulli: (i) the average precipitation (mm) was 1195 mm, equivalent to 5.5 points for the parameter r_{12} (precipitation); (ii) the average temperature (°C) was 13.2 °C, related to 3.5 points for the parameter r_{13} (temperature) (Table 8).
- Temuco: (i) the average precipitation (mm) was 1279 mm, equivalent to 5.5 points for the parameter r_{12} (precipitation); (ii) the average temperature (°C) was 12.8 °C, related to 4.0 points for the parameter r_{13} (temperature) (Table 8).

For the most pessimistic scenario concerning RCP8.5, the maximum amplitude of the results achieved for the deviation in building performance was found in Collipulli. The functionality level of the building COL-02 will increase by 1.51 points; however, another case study (COL-04) presented a decrease of 1.44 points. For the seven case studies examined in Temuco and Collipulli, an average variation of -0.35 was perceived with a standard deviation of 0.93 points (Table 8). Six timber structures presented a decrease in their functional service life between the climatic assessment of 1985–2005 and the forecast for 2044–2069. Only one building (i.e., COL-02) showed an improvement in its functional service life (1.51 points). None of the case studies analysed presented changes in their functional conditions; all maintained their previous conditions.

Notably, with almost the same expected climate change variations, the case studies located in the Araucanía Region mainly observed a decrease in the value of the general functionality index, compared to other southern regions in Chile, such as Los Ríos and Los Lagos, where future climatic changes positively affected the value of the index. This occurred regarding the general functionality of the structures with the same construction characteristics under the most pessimistic climatic scenario: RCP8.5 [38]. However, the existing model has a rather poor sensitivity to changes in climatic parameters, while changes can positively and negatively affect the calculated value of the general function index. Therefore, it would be good to add extreme climatic parameters to the model but for different climatic zones, and these parameters should differ according to trends in the generalised climatic effects. These could include the annual sum of hourly temperatures greater than a specified base temperature as an analogue of cooling degree days; the annual sum of hourly temperatures less than a specified base temperature as an analogue of heating degree days [59,60]; the annual duration of heat waves; the annual duration of frost; the annual sum of direct solar radiation. Concurrently, it is important to consider the effects of climatic parameters and extreme climatic events on the degradation of buildings [61].

This new type of approach can be used for initial state-of-the-art applications considering climate change and the functional degradation conditions of timber heritage buildings in the context of the Southern Hemisphere (e.g., Chile). The results can improve the understanding of buildings' performances in the future. These particular and specific approaches assist in the conceptualisation of a "time–space" examination, showing how climate change effects can affect the future degradation of heritage timber buildings in southern regions of Chile; however, more specific and particular research must be developed. Novel extensive applications must be considered to extend the number of case studies in the region and to examine new contexts considering additional constructive features in extreme cases, such as the northern and extreme southern (Magallanes) regions of South America.

6. Conclusions

This study presented a new approach for recognising the extent to which climatic factors impact the functionality of heritage timber structures, using case studies in two specific cities in the Araucanía Region. Hence, for a consistent analysis of the outcomes obtained, the main restrictions of the fuzzy method applied were explained. The $FBSL_{2.0}$ methodology was previously established to arrange maintenance schedules for heritage parish churches in Andalusia, southern Spain. The system was adjusted and positively applied to new analyses focusing on the functional performance of heritage buildings in south and central Chile [24]; however, the fuzzy system was not previously developed to particularly recognise the impacts of climate change conditions on the functional performance of buildings in any context. Moreover, the model included several input parameters (significant for examining a building's performance) and two variables that especially focused on climatic degradation agents. Furthermore, these two variables (r_{12}—precipitation; r_{13}—temperature) can be applied over time using the new adaptation of the parameters and the valuation involved.

Therefore, several specific conclusions must be drawn after the method's application. The results achieved show that the fuzzy logic system does not recognise meaningful variations in the functional conditions of the timber buildings examined due to the fact of rapid climate changes and because climate changes should arise at a gradual velocity. In addition, the system could detect some variations in the most pessimistic scenario (RCP8.5) for 2044–2069.

Thus, the climatic variations in the region analysed were connected to an expected increase of approximately 1.8 °C in the average temperature and a reduction in the precipitation intensities (171 mm), which could preserve the maintenance of timber buildings at medium/good performance levels. Additionally, in some cases, a particular decrease in the average precipitation quantities could also increase the functional levels (performance) of the timber structures due to the reduction in defects related to water affections.

Examining a larger sample of heritage buildings in the region should induce improvements in the results, although, in previous studies, the number of case studies related to the sample was not an indicator of the sensitivity of the planned fuzzy logic system. This is because, in a city in which approximately 10 structures were examined, the influences of climate change were almost unobserved, while in another location with three or four buildings examined, all presented variations in their estimated functional performance.

In future studies, non-heritage buildings should be examined to detect the impact of climatic conditions. This type of examination will allow for determining whether the current construction methods and the state of the maintenance of buildings significantly impact their resilience and functional performance over time. This analysis helps to assist in developing upcoming strategies and recommendations that can support adaptation policies for managing and controlling architectural heritage regarding climate change forecasts. This information could also be relevant for stakeholders who support the conservation of heritage buildings in new emplacements in south Chile and under the effects of climate change.

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References

1. Ibrahim, F.; Harun, S.H.; Samad, M.H.A.; Harun, W.M.W. Interior Semantics Of The Lobby/Waiting Area In General Hospitals; A Preliminary Study. In Proceedings of the 2nd International Conference On Built Environment In Developing Countries 2008 [Icbed 2008], Penang, Malaysia, 3–4 December 2008; pp. 232–241.
2. Endere, M.L.; Zulaica, M.L. Sustentabilidad Socio-Cultural Y Buen Vivir En Sitios Patrimoniales: Evaluación Del Caso Agua Blanca, Ecuador. *Ambient. Soc.* **2015**, *18*, 265–290. [CrossRef]
3. Prieto, A.J.; Verichev, K.; Carpio, M. Heritage, resilience and climate change: A fuzzy logic application in timber-framed masonry buildings in Valparaíso, Chile. *Build. Environ.* **2020**, *174*, 106657. [CrossRef]
4. Günlü, E.; Pırnar, I.; Yağcı, K. Preserving cultural heritage and possible impacts on regional development: Case of Izmir. *Int. J. Emerg.* **2009**, *1*, 13. Available online: http://www.regionalstudies.org/uploads/networks/documents/tourism-regional-development-and-public-policy/gunlu.pdf (accessed on 8 July 2021).
5. Armitage, L.; Irons, J. The values of built heritage. *Prop. Manag.* **2013**, *31*, 246–259. [CrossRef]
6. 2006 European Comission, NOAH's Ark European Project, (n.d.). Available online: https://ec.europa.eu/regional_policy/en/projects/germany/noahs-ark (accessed on 8 July 2021).
7. C. for Culture, Climate for Culture, (n.d.). Available online: https://www.ohchr.org/Documents/Issues/CulturalRights/Call_ClimateChange/JMassey.pdf (accessed on 8 July 2021).
8. Art-Risk Project, Art-Risk. Artificial intelligence applied to the preventive conservation of heritage buildings, (n.d.). Available online: https://www.upo.es/investiga/art-risk-service/art-risk3/index_en.html (accessed on 8 July 2021).
9. Howard, A.J.; Hancox, E.; Hanson, J.; Jackson, R. Protecting the Historic Environment from Inland Flooding in the UK: Some Thoughts on Current Approaches to Asset Management in the Light of Planning Policy, Changing Catchment Hydrology and Climate Change. *Hist. Environ. Policy Pr.* **2017**, *29*, 1–18. [CrossRef]
10. Balsas, C.J.L. City Centre Revitalization in Portugal: A Study of Lisbon and Porto. *J. Urban. Des.* **2007**, *12*, 231–259. [CrossRef]
11. MINVU. Ministerio de Vivienda y Urbanismo. 2021. Available online: Https://Www.Minvu.Gob.Cl/ (accessed on 8 July 2021).
12. ICOMOS. The Burra Charter: The Australia ICOMOS Charter for Places of Cultural Significance, in: 1999. Available online: http://openarchive.icomos.org/id/eprint/2145/ (accessed on 8 July 2021).
13. Johns, J.; Fedeski, M. Adapting building construction to the effects of climate change. In *Detecting and Modelling Regional Climate Change*; Springer: Berlin/Heidelberg, Germany, 2001; pp. 605–616. [CrossRef]
14. Phillipson, M.C.; Emmanuel, R.; Baker, P.H. The durability of building materials under a changing climate. *Wiley Interdiscip. Rev. Clim. Chang.* **2016**, *7*, 590–599. [CrossRef]
15. Fatorić, S.; Seekamp, E. Are cultural heritage and resources threatened by climate change? A systematic literature review. *Clim. Chang.* **2017**, *142*, 227–254. [CrossRef]
16. Lisø, K.R. Integrated approach to risk management of future climate change impacts. *Build. Res. Inf.* **2006**, *34*, 1–10. [CrossRef]
17. Mechler, R.; Bouwer, L.M.; Schinko, T.; Surminski, S.; Linnerooth-Bayer, J. *Loss and Damage from Climate Change: Concepts, Methods and Policy Options*; Springer Nature: Berlin/Heidelberg, Germany, 2019.

18. Trow, S. The past as a guide to the future: The long-term view. *Conserv. Bull.* **2008**, *57*, 5–7.
19. Sesana, E.; Gagnon, A.S.; Bonazza, A.; Hughes, J. An integrated approach for assessing the vulnerability of World Heritage Sites to climate change impacts. *J. Cult. Heritage* **2020**, *41*, 211–224. [CrossRef]
20. Fundación de Temuco, Ocupación de la Araucanía, Dirección de Bibliotecas, archivos y museos. 2015. Available online: https://www.cultura.gob.cl/wp-content/uploads/2015/08/Informe-Araucan%C3%ADa-final.pdf (accessed on 8 July 2021).
21. Sarricolea, P.; Herrera-Ossandon, M.; Meseguer-Ruiz, Ó. Climatic regionalisation of continental Chile. *J. Maps* **2016**, *13*, 66–73. [CrossRef]
22. CR2, Center for Climate and Resilience Research. 2021. Available online: http://www.cr2.cl/eng/ (accessed on 8 July 2021).
23. Verichev, K.; Zamorano, M.; Carpio, M. Effects of climate change on variations in climatic zones and heating energy consumption of residential buildings in the southern Chile. *Energy Build.* **2020**, *215*, 109874. [CrossRef]
24. Carpio, M.; Prieto, A.J. Methodologies for evaluating the impact of climate aspects on heritage constructions: A Delphi method application. In *Rehabend*; University of Cantabria: Cantabria, Spain, 2020.
25. Rovira, A. Appraising territorial heritage in the region of valdivia. In *Territorial Heritage and Development*; CRC Press: Boca Raton, FL, USA, 2012; pp. 215–230.
26. Guarda, G. Nueva historia de Valdivia, Ediciones Universidad Católica de Chile. 2001. Available online: http://www.memoriachilena.gob.cl/602/w3-propertyvalue-127202.html (accessed on 8 July 2021).
27. Prado, F.; Dalencon, R.; Kramm, F. Arquitectura alemana en el sur de Chile: Importación y desarrollo de patrones tipológicos, espaciales y constructivos. *Revista de la construcción* **2011**, *10*, 104–121. [CrossRef]
28. Saelzer, G. Luis oyarzún house. In *Project of heritage intervention, Dirección de Extensión*; Universidad Austral de Chile and Consejo Nacional de la Cultura y las Artes: Santiago, Chile, 2018.
29. Matthews, M.; Cerda Brintrup, G. *Valdivia en Madera y Metal*; Ediciones: Valdivia, Chile, 1993.
30. Ewert, F. *Arquitectura Patrimonial de La Araucanía: El poblado de Purén*; Universidad del Bío-Bío: Concepción, Chile, 1996.
31. Zadeh, L. Fuzzy sets. *Inf. Control.* **1965**, *8*, 338–353. [CrossRef]
32. Mardani, A.; Hooker, R.E.; Ozkul, S.; Yifan, S.; Nilashi, M.; Sabzi, H.Z.; Fei, G.C. Application of decision making and fuzzy sets theory to evaluate the healthcare and medical problems: A review of three decades of research with recent developments. *Expert Syst. Appl.* **2019**, *137*, 202–231. [CrossRef]
33. Salehi, H.; Burgueño, R. Emerging artificial intelligence methods in structural engineering. *Eng. Struct.* **2018**, *171*, 170–189. [CrossRef]
34. Bernal, J.M.M.; Calama-Rodríguez, J.M.; Chávez-De-Diego, M.-J. Modelo de predicción de la vida útil de la edificación patrimonial a partir de la lógica difusa. *Inf. Construcción* **2014**, *65*, e006. [CrossRef]
35. ISO31000, Risk management—principles and guidelines. 2009. Available online: https://risk-engineering.org/ISO-31000-risk-management/ (accessed on 8 July 2021).
36. Ibáñez, A.J.P.; Bernal, J.M.M.; de Diego, M.J.C.; Sánchez, F.J.A. Expert system for predicting buildings service life under ISO 31000 standard. Application in architectural heritage. *J. Cult. Heritage* **2016**, *18*, 209–218. [CrossRef]
37. Prieto, A.; Verichev, K.; Silva, A.; de Brito, J. On the impacts of climate change on the functional deterioration of heritage buildings in South Chile. *Build. Environ.* **2020**, *183*, 107138. [CrossRef]
38. Prieto, A.J.; Macías-Bernal, J.M.; Chávez, M.J.; Alejandre, F.J.; Silva, A. Impact of maintenance, rehabilitation, and other interventions on functionality of heritage buildings. *J. Perform. Constr. Facil.* **2019**, *33*, 04019011. [CrossRef]
39. Prieto, A.J.; Turbay, I.; Ortiz, R.; Chávez, M.J.; Macías-Bernal, J.M.; Ortiz, P. A fuzzy logic approach to preventive conservation of cultural heritage churches in Popayán, Colombia. *Intern. J. Archit. Herit.* **2020**, 1–20. [CrossRef]
40. C.-I. Centro Nacional de Microelectrónica, Xfuzzy3.0. 2017. Available online: https://www.csic.es/en/investigacion/institutos-centros-y-unidades/centro-nacional-de-microelectronica (accessed on 8 July 2021).
41. C.-I. Centro Nacional de Microelectrónica, Herramientas de CAD para lógica difusa. 2012. Available online: http://www2.imse-cnm.csic.es/Xfuzzy/Xfuzzy_3.3/index.html (accessed on 8 July 2021).
42. Peykani, P.; Mohammadi, E.; Emrouznejad, A.; Pishvaee, M.S.; Rostamy-Malkhalifeh, M. Fuzzy data envelopment analysis: An adjustable approach. *Expert Syst. Appl.* **2019**, *136*, 439–452. [CrossRef]
43. Ng, G.D.; Quek, C. A Novel Financial Decision Support Systems Based on Mendel Type-2 Fuzzy Set Theory. *IJPCC* **2015**, *1*, 1–10.
44. Iancu, I. A mamdani type fuzzy logic controller. In *Fuzzy Logic-Controls, Concepts, Theories and Applications*; BoD–Books on Demand: Hamburg, Germany; CRC Press: Boca Ratón, FL, USA, 2012; pp. 325–350. Available online: https://www.intechopen.com/chapters/34221 (accessed on 8 July 2021).
45. Ross, T.J. *Fuzzy Logic With Engineering Applications*; John Wiley & Sons: West Sussex, UK, 2010.
46. Torres-González, M.; Prieto, A.; Alejandre, F.; Blasco-López, F. Digital management focused on the preventive maintenance of World Heritage Sites. *Autom. Constr.* **2021**, *129*, 103813. [CrossRef]
47. Weber, S. A general concept of fuzzy connectives, negations and implications based on t-norms and t-conorms. *Fuzzy Sets Syst.* **1983**, *11*, 115–134. [CrossRef]
48. Chai, Y.; Jia, L.; Zhang, Z. Mamdani Model Based Adaptive Neural Fuzzy Inference System and its Application in Traffic Level of Service Evaluation. *Int. J. Comput. Intell.* **2009**, *4*, 555–559. [CrossRef]
49. Prieto, A.J.; Macías-Bernal, J.M.; Silva, A.; Ortiz, P. Fuzzy Decision-Support System for Safeguarding Tangible and Intangible Cultural Heritage. *Sustainability* **2019**, *11*, 3953. [CrossRef]

50. Tsai, H.-C.; Lee, A.-S.; Lee, H.-N.; Chen, C.-N.; Liu, Y.-C. An Application of the Fuzzy Delphi Method and Fuzzy AHP on the Discussion of Training Indicators for the Regional Competition, Taiwan National Skills Competition, in the Trade of Joinery. *Sustainability* **2020**, *12*, 4290. [CrossRef]
51. Zhang, K.; Hao, W.-N.; Yu, X.-H.; Jin, D.-W.; Zhang, Z.-H. A Multitasking Genetic Algorithm for Mamdani Fuzzy System with Fully Overlapping Triangle Membership Functions. *Int. J. Fuzzy Syst.* **2020**, 1–17. [CrossRef]
52. Baturone, I.; Barriga, A.; Jimenez-Fernandez, C.; Lopez, D.R.; Sanchez-Solano, S. *Microelectronic Design of Fuzzy Logic-Based Systems*; CRC Press: Boca Raton, FL, USA, 2018. [CrossRef]
53. Tahera, K.; Ibrahim, R.; Lochert, P. A fuzzy logic approach for dealing with qualitative quality characteristics of a process. *Expert Syst. Appl.* **2008**, *34*, 2630–2638. [CrossRef]
54. Prieto, A.J.; Silva, A.; De Brito, J.; Macias-Bernal, J.M. Serviceability of facade claddings. *Build. Res. Inf.* **2017**, *46*, 179–190. [CrossRef]
55. Seo, S.N.; Mendelsohn, R. An analysis of crop choice: Adapting to climate change in South American farms. *Ecol. Econ.* **2008**, *67*, 109–116. [CrossRef]
56. Manatsa, D.; Chingombe, W.; Matarira, C.H. The impact of the positive Indian Ocean dipole on Zimbabwe droughts Tropical climate is understood to be dominated by. *Int. J. Climatol.* **2008**, *28*, 2011–2029. [CrossRef]
57. Haugen, A.; Mattsson, J. Preparations for climate change's influences on cultural heritage. *Int. J. Clim. Chang. Strat. Manag.* **2011**, *3*, 386–401. [CrossRef]
58. Vera, C.; Silvestri, G.; Liebmann, B.; Gonzalez, P. Climate change scenarios for seasonal precipitation in South America from IPCC-AR4 models. *Geophys. Res. Lett.* **2006**, *33*, 1–4. [CrossRef]
59. Mourshed, M. Relationship between annual mean temperature and degree-days. *Energy Build.* **2012**, *54*, 418–425. [CrossRef]
60. Verichev, K.; Carpio, M. Climatic zoning for building construction in a temperate climate of Chile. *Sustain. Cities Soc.* **2018**, *40*, 352–364. [CrossRef]
61. Barrelas, J.; Ren, Q.; Pereira, C. Implications of climate change in the implementation of maintenance planning and use of building inspection systems. *J. Build. Eng.* **2021**, *40*, 102777. [CrossRef]