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Expert Panel, Preventive Maintenance of Heritage Buildings and Fuzzy Logic System: An Application in Valdivia, Chile

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Abstract: The maintenance of buildings is a highly complex decision process, which is generally due to professional experts having to consider several arduous evaluations, especially regarding uncertainty related to why, when and how to intervene. This study concerns the analysis of the uncertainty associated with professional experts' surveys during the decision-making process during building maintenance. For this purpose, a case study of a timber-structure building was examined. An expert panel of 66 professionals with expertise in construction engineering carried out a systematic and automated evaluation. This kind of digital method is capable of managing the uncertainty associated with the evaluation processes by different specialists. Experts can evaluate various nuances and approximations in the model's input parameters. The fuzzy model helps to harmonize the results since minor variations in the evaluation of the input parameters do not generate a large dispersion over the model's output variable. The novelty of this study concerns the application of a digital methodology based on a fuzzy logic model to assist a professional expert panel in different areas—architecture, engineering and construction. This study is oriented through an artificial intelligence based method applied by specialists to set intervention priorities, support maintenance management of the examined building and minimise human error during data collection and uncertainty related to making decisions. The lessons learned from the results obtained in this study promote the use of this kind of digital tool to manage the uncertainty associated with in-situ visual inspections.

Keywords: fuzzy system; uncertainty; expert panel; decision-making; timber structure; building

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1. Introduction

Complex socio-technical decisions, such as when to intervene on heritage structures, or more so, a heritage building or set of buildings, is based on a considerable amount of evidence, information an even records handled and collected by multidisciplinary professional panels [1]. The information needed for the decision-making process about the future state of a building is often ambiguous, incomplete and presents a degree of uncertainty [2]. Moreover, the inadequate performance of buildings during their whole period of service life normally involves an exceptionally high economic and social load [3]. Concerning a worldwide scale, the built heritage is aged and with clear signs of deterioration. The current state is due to the lack of standards for the continued management of buildings during their period of service life, the lack of investment in built heritage rehabilitation and also a lack of knowledge and tools focused on decision-making [4].

Buildings and components naturally deteriorate over time, with a continuing degradation of their performance state until the point at which they are no longer capable of satisfying the users' needs and supplies [5]. Chen et al. stated that the safeguarding of the buildings' performance condition for a longer period through the mitigation of their degradation depends on decisions involving several preventive maintenance tasks [6]. The lack of decision-making tools for the optimisation of preventive maintenance activities in heritage buildings lead to excessive and even unnecessary costs due to the performance of inefficient and inadequate maintenance operations [7].

In terms of minimising the excessive costs related to reactive maintenance events, stakeholders are currently implementing predictive or condition-based maintenance plans [8]. The main aim of buildings' maintenance activities is to ensure that their systems and components always function adequately, with the intention of achieving optimum performance during their life cycle [9]. Predictive maintenance is based on the assessment of the assets' condition, intending to reduce unexpected failures and consequently decrease maintenance budgets [10]. Therefore, maintenance activities must be understood as an investment opportunity that needs to be improved and optimised and not as a cost that must be minimised. Moreover, subjective aspects that are crucial for the decision-making process, such as the users' perception, needs and expectations, and the funds available, should also be considered in the definition of maintenance policies. Alba-Rodríguez et al. declared that the key criteria for decision-making in regard to the buildings' renovation are the investment costs, the buildings' performance situations, existing guidelines and the minimisation of uncertainty linked to degradation buildings' procedures [11].

In different engineering situations, the stakeholders are faced with a lack of data and incomplete data and material for modelling certain real-world phenomena [7]. In this regard, uncertainty is one of the knowledge aspects [12]. In this sense, decision-making processes and performance evaluation in engineering [13], especially in processes with a significant degree of uncertainty involved have been broadly analysed and examined using fuzzy theory. Fuzzy logic systems are still considered as ground-breaking procedures for modelling real-world phenomena [14], especially when there exists a certain degree of vague and uncertainty, i.e.,: such as the case of modelling heritage buildings' degradation [15]. Regarding this approach, the methodology used by professionals can forecast the functionality of buildings associated to service life prediction overtime. This method is grounded on the fuzzy set theory founded in 1965 by Zadeh [16].

In the scientific field, a panel of experts can analyse the strengths and weaknesses of a model. This methodology is used in different disciplines of knowledge such as medicine [17,18]; engineering [19,20]; business [21]; heritage [22,23]; COVID-19 [24]; etc.

The main novelty of this research work considers the application of a digital methodology based on a fuzzy logic model to assist a professional expert panel in different areas—architecture, engineering and construction (AEC). This study has been oriented through an artificial-intelligence-based method applied by specialists to set intervention priorities, support maintenance management of the examined building and minimise both human error during data collection and the uncertainty associated with making decisions [25].

Thus, the main objective considers the uncertainty analysis in decision-making of vulnerability and risk variables associated with a digital management model based on fuzzy logic. To keep training the model, a case study—Haverbeck House in Valdivia, Chile—was specifically analysed in detail by a panel of experts.

2. Materials and Methods

In Figure 1, the research methodology is summarized into six principal steps.

2.1. Case Study Characterisation and Emplacement

The geographical location of Valdivia (South Chile) corresponds to latitude 39°48′30″ S and longitude 71°14′30″ W. The elevation of the city is around 5 m (Figure 2). Regarding the climatic location of the city of Valdivia and based on the Köppen–Geiger Cfb categorisation, Valdivia presents a climate—Marine West Coast, with dry and warm summers seasons as well as oceanic influence effects [26–30]. The maximum annual precipitation values exceed 1770 mm, and the highest average annual temperature (1975–2004) observed in Valdivia is just over 11.0 °C.

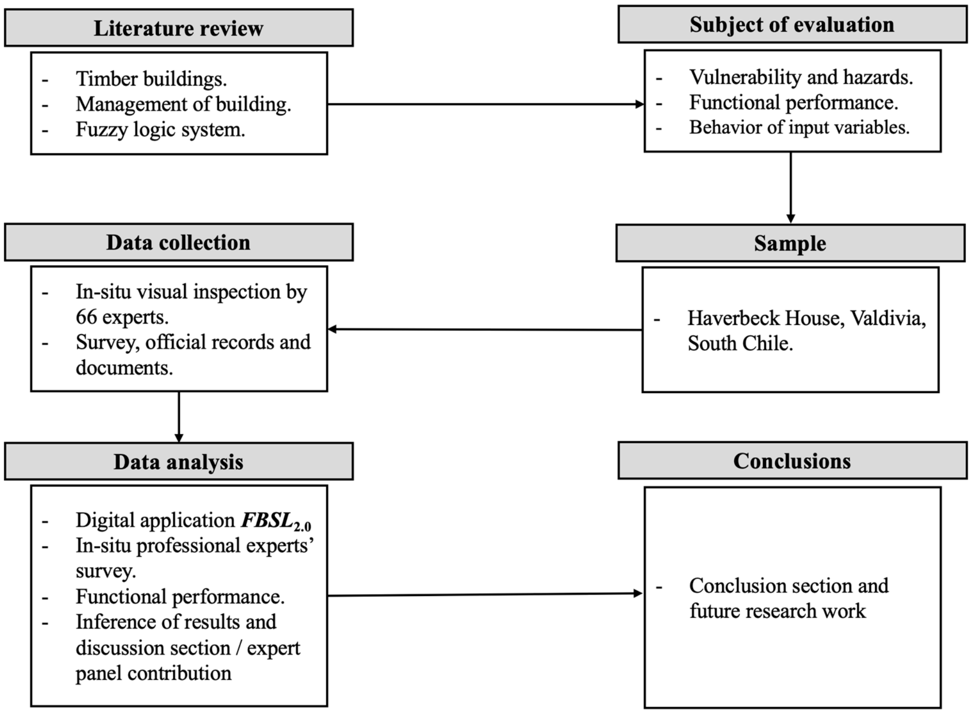


Figure 1. Research methodology.

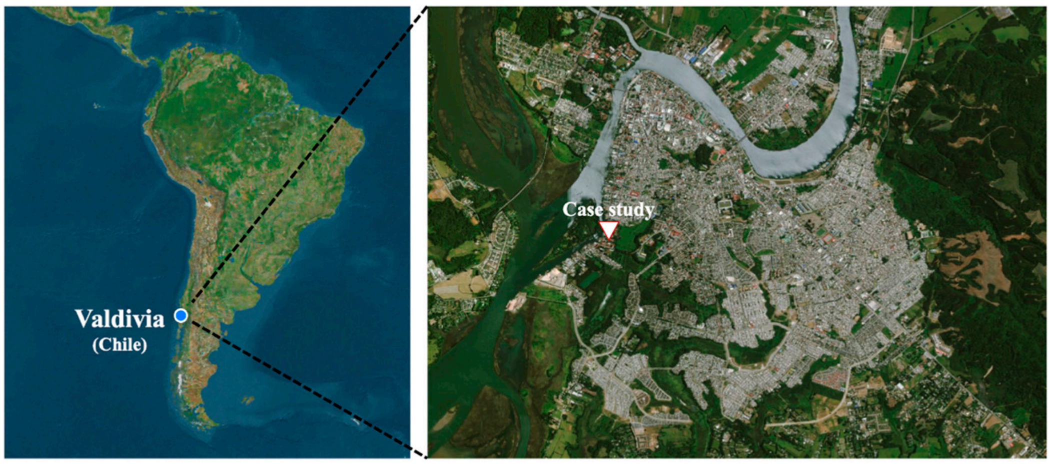


Figure 2. Emplacement of the case study in South America and in the city of Valdivia (South Chile).

The case study under analysis is emplaced in the Miraflores area in the south sector of the city of Valdivia in Chile (Figure 2). Figure 3 shows the current state of the maintenance of the Haverbeck House—the case study—with several pictures. Figure 4 shows the distribution of areas of the first (203.65 m^2) and the second floor (92.58 m^2) of the building under analysis. Figure 5 shows the four elevations corresponding to the cardinal points of the orientation. The building has a timber structure and stands out for some of the following construction characteristics [31–33] (Figure 3): The building has a corridor just in front of the entrance hall that distributes the different access to rooms and chambers. The plans of the building are rectangular. The building has two storeys above ground—first and second floor—and a store on the ground floor, which is disabled. Foundations were provided using wooden beams reinforced by concrete and timber logs. The building has a structure based on timber beams and pillars, mainly used post-and-beam construction system. The first floor has a greater height than the ground floor and second floor.

Figure 3. Pictures of the case study under analysis.

Figure 4. Architectural plan of the Haverbeck House.

As shown in Figure 4, the Haverbeck House is divided mainly into two floors. Next, the use and surface of each area—17 areas on the first floor and 10 areas on the second floor—of the house are indicated. Regarding the ground floor, it is does present any uses and divisions.

First floor: (1) Waiting room (14.56 m^2); (2) Bathroom 1 (2.66 m^2); (3) Bathroom 2 (2.18 m^2); (4) Hall (4.43 m^2); (5) Kitchenette 1 (4.87 m^2); (6) Office 1 (21.06 m^2); (7) Kitchenette 2 (7.64 m^2); (8) Kitchenette 3 (9.79 m^2); (9) Office 2 (19.63 m^2); (10) Corridor (20.96 m^2); (11) Meeting room (28.02 m^2); (12) Kitchenette 4 (2.02 m^2); (13) Office 3 (16.45 m^2); (14) Office 4 (30.02 m^2); (15) Office 5 (14.31 m^2); (16) Kitchenette 5 (2.13 m^2); and (17) Bathroom 3 (2.92 m^2).

Second floor: (1) Hall (4.83 m^2); (2) Corridor (12.42 m^2); (3) Kitchenette (12.95 m^2); (4) Meeting room (11.47 m^2); (5) Module office 1 (5.38 m^2); (6) Service area (6.32 m^2); (7) Module office 2 (9.88 m^2); (8) Module office 3 (9.92 m^2); (9) Module office 4 (9.68 m^2); and (10) Module office 5 (9.73 m^2).

Figure 5. Architectural elevations of the Haverbeck House.

2.2. Definition of the Fuzzy Inference System

This fuzzy methodology is particularly relevant when the modelled problem is subject to considerable uncertainty [34,35]. In this way, this type of system is able to model real-world phenomena [16].

The model—fuzzy building service life extended version ($FBSL_{2.0}$)—was initially developed by the University of Seville (Spain) [36], which considered the analysis of the functional degradation of heritage parish churches located in the context of Andalusia, South Spain. The methodology was implemented in Xfuzzy 3.0 [37], an open access software application. The last fuzzy model upgrades are concerned with a standardisation with the international standard focused on risk management ISO 31000:2021 [38,39]. The fuzzy logic system ($FBSL_{2.0}$) was also validated and correlated to another predictive method, which evaluates the physical degradation of the building components. The results demonstrated that when the degradation of the building components increases, their functionality index decreases. To perform this analysis, the degradation condition of 647 claddings (203 natural stone claddings, 183 ceramic claddings, 177 painted surfaces and 84 rendered façades), located in the Almada, Lisbon and Algarve regions of Portugal, were examined. A strong relationship between the two indexes considered was obtained (with a determination coefficient of 0.756 for natural stone claddings, 0.764 for ceramic claddings, 0.833 for painted surfaces and 0.673 for rendered façades), revealing an inverse correlation between both predictive methodologies [40]. Moreover, the model was applied to analyse the buildings' functionality over several decades by examining the historical refurbishment and maintenance actions performed [41]. This led to the identification of the most common anomalies over the years, the probable causes and the frequency and adequacy of the maintenance and rehabilitation actions performed.

The fuzzy inference methodology ($FBSL_{2.0}$) used in this study can be defined by: (i) functional buildings parameters (vulnerabilities and external hazards) (Table 1); (ii) fuzzification stage; (iii) knowledge base and inference rules; (iv) defuzzification stage; and (v) output variable related to the level of the building's performance.

Table 1. Fuzzy logic system input parameters [36].

Vulnerability and External Risk	Variables' Nomination	Range
Vulnerability input parameters	Geological location (v_1)	(1, 4) [1]
	Roof design (v_2)	(1, 8) [2]
	Environmental conditions (v_3)	(1, 8) [2]
	Construction system (v_4)	(1, 8) [2]
	Preservation (v_5)	(1, 8) [2]
Static-structural input parameters	Load state-modification (r_6)	(1, 8) [2]
	Live loads (r_7)	(1, 8) [2]
	Ventilation (r_8)	(1, 8) [2]
	Facilities (r_9)	(1, 8) [2]
	Fire (r_{10})	(1, 8) [2]
	Inner environment (r_{11})	(1, 8) [2]
Atmospheric input parameters	Precipitations (r_{12})	(1, 8) [2]
	Temperature (r_{13})	(1, 8) [2]
Anthropic input parameters	Population growth (r_{14})	(1, 8) [2]
	Heritage value (r_{15})	(1, 8) [2]
	Furniture value (r_{16})	(1, 8) [2]
	Occupancy (r_{17})	(1, 8) [2]

[1] Minimum (1.0—favourable) and maximum (4.0—unfavourable) valuations regarding the input parameter (v_1).
[2] Minimum (1.0—favourable) and maximum (8.0—unfavourable) valuations regarding the input parameters ($v_{2\text{–}5}$ and $r_{6\text{–}17}$).

Fuzzification stage. This the first step in the definition of the fuzzy expert system. The inputs (Table 1) and output are defined and characterized. The set of 17 input parameters are fuzzified regarding membership functions μA. The universe of discourse (U), in which a fuzzy set can have any possible valuation in the range of (0, 1), which is defined in Equation (1):

$$\mu A\ (u) : U \rightarrow B\ [0, 1] \tag{1}$$

A membership function μ assigns a degree of membership to each element in a fuzzy set A, ranging from the value 0 to the value 1 [42]. Membership functions related to Gaussian-type were stated in the total of input parameters, except in the membership function of the input variable v_1 (geological location); this membership function is trapezoidal (it establishes four types of terrain—optimum, medium, bad, very bad). In this sense, each kind of terrain corresponds to a membership function. Gaussian- type membership functions are generally used, as they are considered the most appropriate for modelling the degradation conditions of buildings and also because a non-zero value can be reached at all points [42].

The fuzzy inference system uses the fuzzy operator "and" as connector, which is defined as an intersection. Thus, given two sets A and B, defined on their respective universes of discourse U, the intersection of both sets is a fuzzy set $A\,\hat{}\,B$, whose membership function is defined in Equations (2) and (3):

$$\mu A \wedge\ B\ (x,\ y) = T[\mu A(x),\ \mu B(y)] \tag{2}$$

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

where T(x,y) = T-norm that complies with the commutative, associativity and monotony properties, as seen in Equation (2). The FBSL$_{2.0}$ method uses the minimum as connective [43].

Regarding the definition of the set of 17 input parameters of the model, a set of 15 professional experts in the area of heritage building management were consulted during the model's design stage. In this sense, a Delphi method, using Opina software (owned by the University of Seville, Spain), was used to obtain experts' survey. The experts consulted in this study presented the following profiles [36] with numerous publications on this subject [44].

Base of knowledge and inference rules. The base of knowledge, fuzzy rules and hierarchical structure were established considering a professional expert survey, which has been previously described. The fuzzy model is based on the inference system of Mamdani [43]. Grima and Babuška stated that these types of artificial intelligence systems can be defined as semi-transparent models. In this sense, this fuzzy logic system is able to describe the relationship between the set of input parameters and the output parameter using *if-then inference* rules [45]. The professional expert survey established a total of 354 rules, and they also defined the combinations between input membership functions and output membership functions. Logical reasoning techniques allow for drawing conclusions from a set of logical rules and a set of observations. The most important method of fuzzy logic inference is known as generalised modus ponens. Each fuzzy rule establishes $\ll$ if x is A then y is $B \gg$ and the observation $\ll x$ is $A' \gg$, $\ll y$ is $B' \gg$—this conclusion is obtained where the fuzzy set B' is closer to B, when A' is closer to set A [46]. Based on the inference mechanism defined in Equations (4) and (5), $\text{FBSL}_{2.0}$ can be determined by the combination of the different rules for the variables included in the model.

$$R(1) : IF\ x_1\ is\ A_1^1\ AND\ x_2\ is\ A_2^1 \ldots\ x_n\ is\ A_n^1\ THEN\ y\ is\ B^1 \tag{4}$$

$$R(t) : IF\ x_1\ is\ A_1^t\ AND\ x_2\ is\ A_2^t \ldots\ x_n\ is\ A_n^t\ THEN\ y\ is\ B^t \tag{5}$$

Defuzzification. The defuzzification method 'centre of gravity' was adopted in the design step of the fuzzy method ($\text{FBSL}_{2.0}$). This defuzzification approach is one of the most considerably utilised in engineering. A Riemann sum [47] allows the functional index ($\text{FBSL}_{2.0}$) of the heritage buildings to be estimated under analysis (Equation (6)):

$$FBSL_{2.0} = \frac{\sum_i y_i\ \mu B(y_i)}{\sum_i\ \mu B(y_i)} \tag{6}$$

Concerning the output variable of the fuzzy system ($\text{FBSL}_{2.0}$), three levels were performed based on the international standard of risk management ISO 31000:2011 [39,48]:

Condition level A—(Range 51, 30): Building presents an adequate functional level. No intervention is needed.

Condition level B—(Range 30, 20): Building displays a situation in which the costs and benefits of preventive measures must be taken into account and balanced. Periodical inspections are recommended.

Condition level C—(Range 20, 09): Building presents a high priority of intervention.

The output of the functional service-life model ($\text{FBSL}_{2.0}$) is dimensionless since it provides as output a 'functionality index', which is a ranking of the priorities of intervention between the set of buildings considered. Therefore, it is not possible to arithmetically quantify the accuracy of the model or the prediction errors, since the model addresses a semi-qualitative index, based on the evaluation by experts of the risks and vulnerabilities of each building analysed. In this sense, the uncertainty of this model is addressed as a type B uncertainty [49], i.e., the model is based on the technical-scientific judgment of 15 experts specializing in the maintenance and conservation of heritage buildings.

2.3. Characterisation of the Expert Panel

In the present study, 66 professionals participated in the expert panel. All the experts had the following characteristics in common: (i) university education; (ii) having the necessary training to carry out the inspection methodically; and (iii) experience in the area. Among the experts, 36.3% had postgraduate degrees—24.2% Master's and 12.1% PhD. All the experts were engineers but with different specialties: Environmental Engineering (1.5%); Chemical Engineering (1.5%); Mechanical Engineering (1.5%); Transportation Engineering (3.0%); Operations Research Engineering (4.5%); Hydraulic Engineering (6.1%); Structural Engineering (22.8%); and Construction Engineering (59.1%).

3. Results and Discussion

The first subsection describes a visual inspection by the expert panel. The second subsection concerns the analysis of the input variables' valuation in the fuzzy inference system. Finally, third subsection contains a detailed analysis in terms of the output variable.

3.1. Visual Inspection of the Haverbeck House Regarding an Expert Panel

During their visual inspection of the case study, the expert panel fulfilled their assessment of the fuzzy logic model input parameters (vulnerability and external risks affections) [50]. The principal aim of this approach was to improve data collection through on-site inspection.

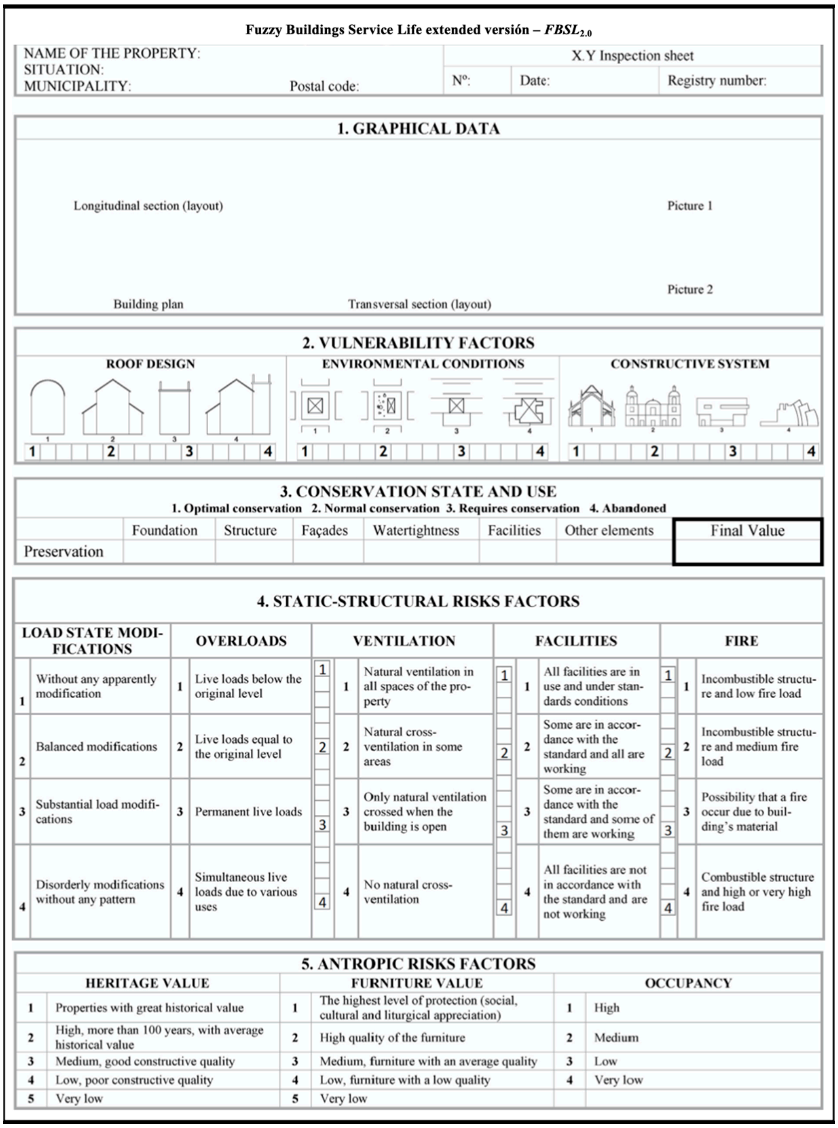
The evaluation presented in Table A1, related with the Haverbeck House corresponds to the assessment made by the set of 66 professional experts, during the visual inspection virtual and in-situ, which evaluates the set of 17 inputs variables using a more extensive file with the detailed explanation of each variable and an inspection sheet (Figure 6) for the registration of the observed condition of the building.

Five of the input variables (one vulnerability variable and four hazards) represented fixed environmental conditions and are thus constant in this particular real simulation (Table 1): v_1—geological location corresponds to 4.0 (unfavourable); r_{11}—inner environment is 5.0 (medium valuation); r_{12}—precipitations is 6.0 (high valuation); r_{13}—temperature is 5.0 (medium valuation); and r_{14}—population growth is 4.0 (low/medium valuation). The remaining 12 parameters, four related to intrinsic vulnerability and eight external hazards, were evaluated by visual inspection. In this work, the data incorporates different kinds of documents and evidence from the current administrative owner institution, which also includes organizational strategic plans, annual reports and preservation surveys [51]. These field examinations allow a better and deeper understanding of different aspects i.e., built environment, historical features, conditions of property, constructive system and structural current situation, among others [51].

3.2. Analysis of the Input Variables' Valuation by Expert Panel

Table A1 shows the results of the in-situ visual inspection performed by the expert panel. The following analysis regards the valuation difficulties registered by the expert panel during their inspection and in terms of the vulnerability and hazard input variables of the fuzzy model ($FBSL_{2.0}$). Thus, the input parameters, which presented high dispersion during the inspection stage, were especially examined. This kind of analysis can help specialists in the area of AEC to identify input variables easily, including those that are difficult to evaluate [53].

Standard deviation (SD) is one of the most common measures of dispersion, which indicates how dispersed the data are from the mean value [54]. A higher SD will correspond to a higher dispersion of a data set. Figure 5 shows a total of four box plots representing the vulnerability input parameters (v_2, v_3, v_4 and v_5). The maximum value for each input variable was 5.0 for roof design (v_2), 6.0 for environmental conditions (v_3), 8.0 for construction system (v_4) and 8.0 for preservation (v_5). The minimum valuations were 3.0 for (v_2), 1.0 for (v_3), v_4 was 1.0 and v_5 was 2.7. Environmental conditions and construction system had the lowest valuations, while preservation is the vulnerability input variables with the highest valuation (Figure 7). The average value of each input parameter was 3.50 for roof design (with a SD of 0.60 and concerning a 95 percent of confidence interval (CI) of $\pm$0.14 points); 2.50 for environmental conditions (SD = 1.26 points; 95% CI = $\pm$0.30 points); 3.7 for construction systems (SD = 1.41 points; 95% CI = $\pm$0.34 points); and 5.2 for preservation (SD = 1.24 points; 95% CI = $\pm$0.30 points).



Fuzzy Buildings Service Life extended versión – *FBSL*$_{2.0}$

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

1. GRAPHICAL DATA

Longitudinal section (layout) Picture 1

Picture 2

Building plan Transversal section (layout)

2. VULNERABILITY FACTORS

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

3. CONSERVATION STATE AND USE

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

	Foundation	Structure	Façades	Watertightness	Facilities	Other elements	Final Value
Preservation							

4. STATIC-STRUCTURAL RISKS FACTORS

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

5. ANTROPIC RISKS FACTORS

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

Figure 6. Fuzzy logic system inspection sheet used by the expert panel during the in-situ visual inspection [52].

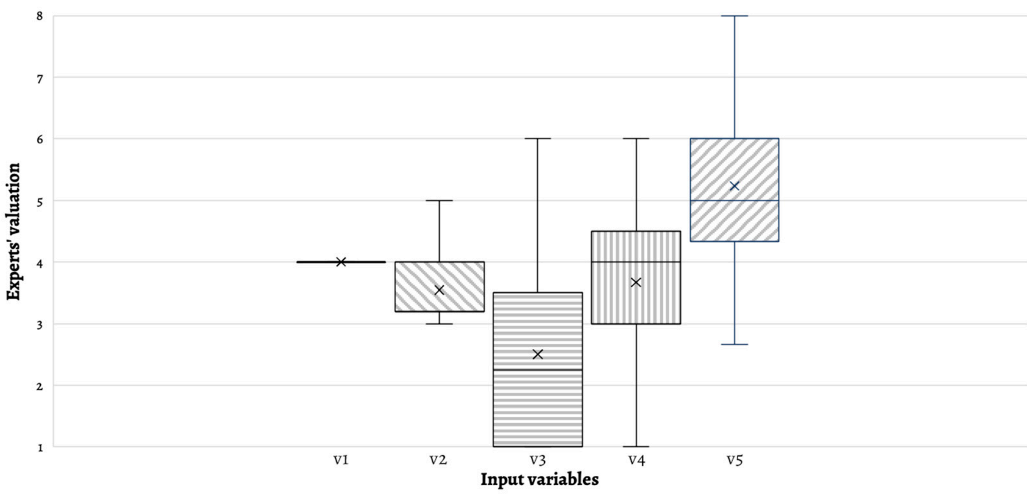


Figure 7. Dispersion analysis of the vulnerability parameters of the digital fuzzy model from professional experts' valuations.

Figure 8 shows a total of eight box plots according to the hazard input parameters ($r_{6–10}$, and $r_{15–17}$). The maximum value for each hazard variable was 8.0 for load state-modification (r_6), 8.0 for live loads (r_7), 8.0 for ventilation (r_8), 6.0 for facilities (r_9), 8.0 for fire (r_{10}), 8.0 for heritage value (r_{15}), 8.0 for furniture value (r_{16}) and 6.0 for occupancy (r_{17}). The minimum valuation of the eight input variables related to external hazard effects was 1.0 point (Figure 6). The average value in each input parameter was 4.30 for load state-modification (with a SD of 2.12 points and a 95% confidence interval (CI) of ±0.51 points); 4.90 for live loads (SD = 1.76 points; 95% CI = ±0.42 points); 4.10 for ventilation (SD = 1.49 points; 95% CI = ±0.36 points), 3.10 for facilities (SD = 1.37 points; 95% CI = ±0.33 points), 5.60 for fire (SD = 1.33 points; 95% CI = ±0.32 points), 3.10 for heritage value (SD = 1.58 points; 95% CI = ±0.38 points), 4.60 for furniture value (SD = 1.68 points; 95% CI = ±0.41 points) and 3.10 occupancy (SD = 1.52 points; 95% CI = ±0.37 points).

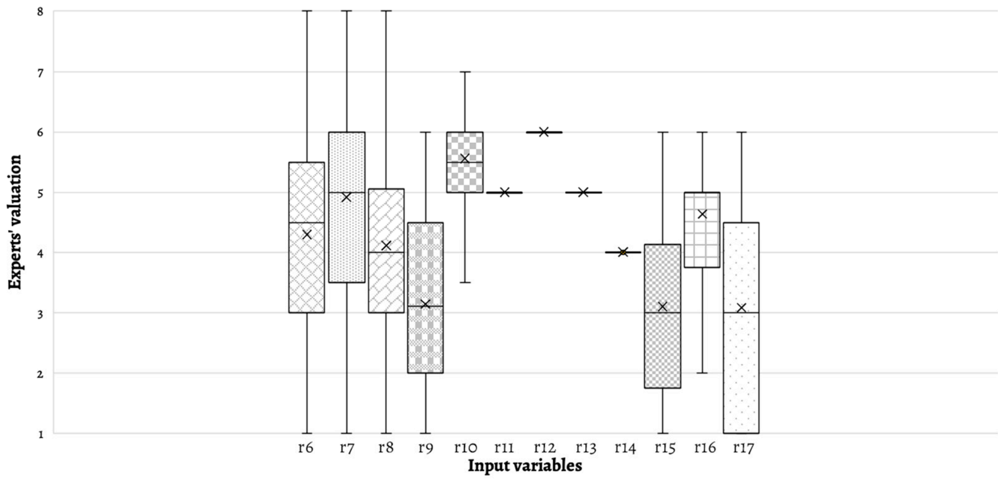


Figure 8. Dispersion analysis of the hazard parameters of the digital fuzzy model from professional experts' valuations.

Summarizing this practical study, the highest SD (±2.12) (CI = ±0.51) was identified for the input variable r_6 (load state-modification), followed by r_7 (live loads) with a SD of ±1.76 (CI = ±0.42), r_{16} (furniture value) (SD = ± 1.67; CI = ±0.41) and r_{15} (heritage value) with a SD of ± 1.58 (CI = ±0.38). The input variable with the lowest SD (±0.57) (CI = 0.14) was v_2, roof design, which is the parameter with the greatest weight in the fuzzy logic model ($FBSL_{2.0}$) [53]. Low SDs were seen in the valuations of v_5 (preservation), v_3 (environmental conditions) and r_{10} (fire) (±1.24 (CI = ±0.30), ±1.26 (CI = ±0.30), and ±1.33 (CI = ±0.32), respectively). This approach helps in examining the valuation of the parameters in the digital system ($FBSL_{2.0}$) and their consequences over the output variable (functionality of buildings).

3.3. Analysis of the Output Parameter of the Fuzzy Logic Methodology

In the analysis of the functional degradation of Haverbeck House, some assumptions must be considered. For the real-world application of the digital system ($FBSL_{2.0}$) in the South Chile, a sensitivity simulation evaluation for ranging the maximum possible values and minimum possible values of the system had been previously stated by Prieto et al. [55]. The fuzzy system examination confirmed that the lowest possible value of the fuzzy system output is nine points that was also achieved in a previous real-world analysis in southern Europe (Portugal and Spain) and South America. The upper possible valuation regarding the functional degradation output was founded as 51 points, for buildings emplaced in the southern context of Chile [55].

From the output model (functional degradation) (Table A1), 22.73% of the expert panel obtained the highest functionality level, i.e., condition A, in which the building presents an adequate functional level. No intervention is needed (Table A1). From the panel of experts, 72.73% rated the Haverbeck House as having condition B, in which the building displays a situation in which costs and benefits of preventive measures must be taken into account and balanced. Periodical inspections are recommended (Table A1). The remaining 4.54% of the expert survey gave the lowest functionality degradation level, i.e., condition C, in which the building presents a high priority of intervention (Table A1). Figure 9 shows the dispersion analysis of the output digital fuzzy model parameter. The average functional service life was 26.0 with a SD of 5.52 points and a 95% CI of ±1.33 points.

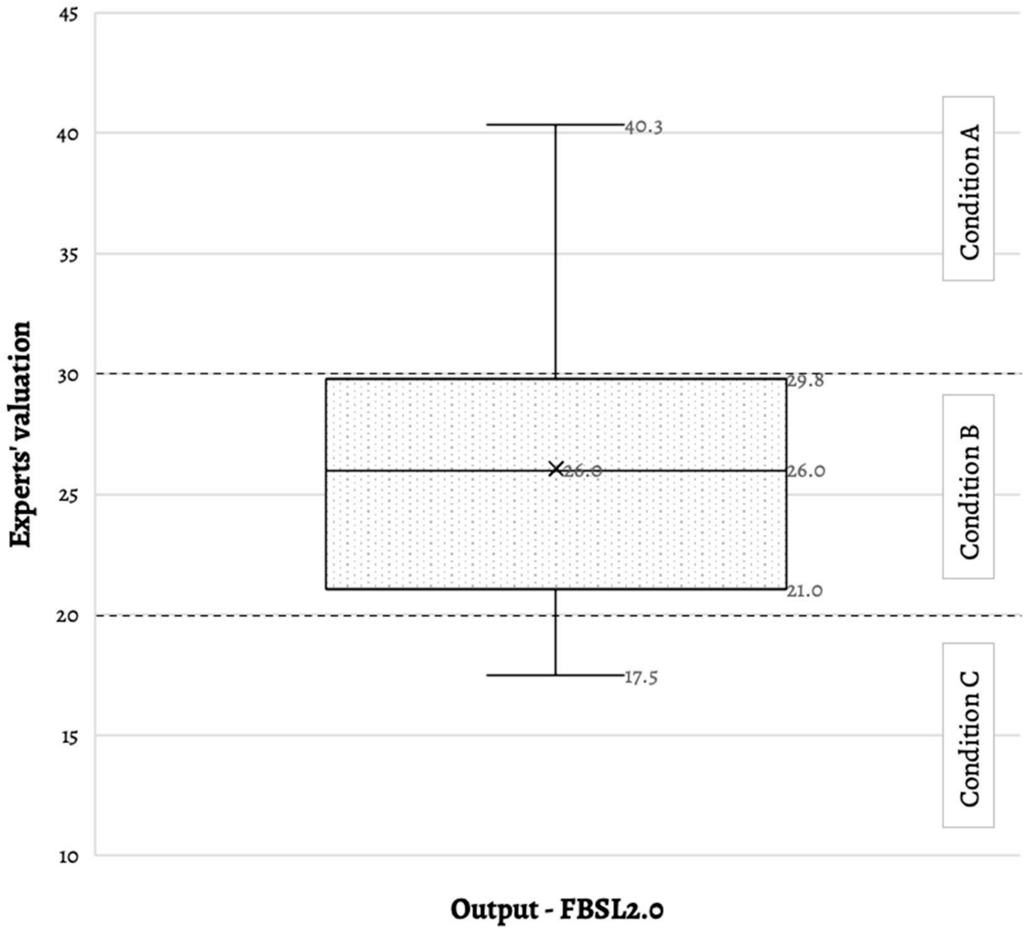


Figure 9. Dispersion analysis of the output variable of the fuzzy system after professional experts' survey.

After this application, the results show good usability of the fuzzy system and a short learning curve, which means that professional experts with little or no experience using the fuzzy logic system could apply and obtain results according to expectations [56].

3.4. Discussion of the Results

Concerning this study, some issues may be discussed: (i) this kind of fuzzy logic system are able to manage the dispersion asset in a set of expert panel and this model can produce coherent and normalised results in terms of the issue under analysis in this case: the functional valuation of a heritage building located in South Chile; (ii) the implementation of more experts in the process will help in understanding the behaviour of this type of fuzzy systems when hundreds or thousands experts using the same system, at the same time, in the same building; (iii) this application can be extrapolated to another case studies, in different environmental, social and cultural contexts; and (iv) regarding the limitations of the study, it was corroborated that the applicability of the system has to be supported in a brief induction in terms of the explanation of the fuzzy system and the input variables of the model.

4. Conclusions

This study involved an expert panel of 66 professionals who visually inspected the Haverbeck House, a heritage building emplaced in Valdivia, South Chile. This approach is innovative in that it considers a set of experts in a detailed evaluation of the functional performance of a specific heritage building in Chile.

Regarding the input parameters of the fuzzy logic model, three input variables were identified to have the lowest valuation dispersion during the inspection stage by the expert panel: (input parameter related to roof design—v_2, environmental conditions—v_3, and preservation—v_5). These variables represent significant weights in the fuzzy logic model. However, r_{17} (occupancy) had a medium–high dispersion of the expert panel's valuations; therefore, this input variable must be examined in detail in future works due to its important weight in the fuzzy inference system. Such expert-panel-based approaches can help in the improvement of input variable valuation during in-situ inspection stage. This approach contributes to the examination of the valuation of input parameters in the fuzzy logic model ($FBSL_{2.0}$) and their consequences over the output variable (functional degradation). Considering a limitation identified during the in-situ visual inspection, it was corroborated that the applicability of the system must be supported in a brief induction in terms of the explanation of the fuzzy system and the valuation of the input variables of the model.

From the output of the model, 72.73% specialists considered the Haverbeck House to be in condition B, in which the building displays a situation in which costs and benefits of preventive measures must be taken into account and balanced. Periodical inspections are recommended. This kind of digital method, based on fuzzy logic, supports the management and reduction of uncertainty in building degradation processes and aids in the reduction of uncertainty during the in-situ inspection of buildings. Despite the fact that different experts can evaluate a building in various ways, the fuzzy logic method is able to help in the minimisation of uncertainties in the process and results. The information gained in this study is crucial since the fuzzy set method (digital management system) can be used by diverse stakeholders and different end-users in the AEC sector, thereby supporting an efficient digital system for preserving historical buildings. In future research studies, the fuzzy method could be applied to new case studies (heritage or non-heritage buildings) and contexts with new expert panels and including adaptation to other potential circumstances, components and environmental settings.

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Appendix A

Table A1. Input parameters and output parameter of the digital fuzzy model ($FBSL_{2.0}$) from the evaluations of 66 professional experts.

	Inputs																	Output	
	Vulnerabilities Variables					*External Hazards Variables*													
Expert ID	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}	$FBSL_{2.0}$	Condition
24	4.0	3.2	3.5	3.2	3.8	1.0	1.0	3.5	1.0	5.5	5.0	6.0	5.0	4.0	3.0	5.0	5.0	43.5	A
11	4.0	3.2	1.0	3.2	2.7	3.5	3.5	4.5	3.2	4.8	5.0	6.0	5.0	4.0	2.5	8.0	1.0	40.3	A
26	4.0	3.2	3.5	5.5	4.3	1.0	3.5	3.5	3.5	3.5	5.0	6.0	5.0	4.0	3.0	2.5	3.0	36.4	A
9	4.0	3.2	1.0	3.2	4.3	1.0	5.5	5.5	3.5	1.0	5.0	6.0	5.0	4.0	1.0	8.0	1.0	35.4	A
46	4.0	4.0	2.0	4.5	3.0	6.0	5.0	3.0	3.0	6.0	5.0	6.0	5.0	4.0	3.0	8.0	3.0	34.5	A
22	4.0	3.2	2.8	2.2	3.8	3.5	3.5	4.5	4.5	6.0	5.0	6.0	5.0	4.0	5.0	5.0	3.0	33.8	A
7	4.0	3.2	3.5	5.5	3.7	1.0	3.5	3.5	3.5	5.5	5.0	6.0	5.0	4.0	1.0	5.0	1.0	32.8	A
3	4.0	3.2	1.0	3.2	4.5	1.0	3.5	5.5	3.5	5.5	5.0	6.0	5.0	4.0	1.0	5.0	1.0	31.1	A
10	4.0	3.2	1.0	3.2	4.7	1.0	5.5	3.5	3.5	5.5	5.0	6.0	5.0	4.0	1.0	5.0	1.0	31.1	A
6	4.0	3.2	3.5	1.0	4.8	1.0	8.0	1.0	3.5	8.0	5.0	6.0	5.0	4.0	3.0	5.0	1.0	30.7	A
21	4.0	3.2	3.5	4.0	4.0	3.5	3.5	3.5	1.0	5.5	5.0	6.0	5.0	4.0	5.0	3.0	3.0	30.7	A
28	4.0	3.2	1.0	1.0	4.2	3.5	5.5	3.5	1.0	5.5	5.0	6.0	5.0	4.0	1.0	5.0	1.0	30.4	A
20	4.0	3.2	3.5	3.2	4.3	8.0	5.5	3.5	3.5	5.5	5.0	6.0	5.0	4.0	1.0	3.0	1.0	30.1	A
23	4.0	3.2	3.5	3.2	3.6	3.5	1.0	3.5	1.0	5.5	5.0	6.0	5.0	4.0	3.0	1.0	5.0	30.1	A
4	4.0	3.2	3.5	3.2	4.6	5.5	5.5	5.5	3.5	5.5	5.0	6.0	5.0	4.0	1.0	5.0	1.0	30.0	A
15	4.0	3.2	2.5	4.0	4.4	3.5	3.5	3.5	3.5	5.5	5.0	6.0	5.0	4.0	1.0	8.0	3.0	29.9	B
18	4.0	3.2	3.5	2.2	4.0	8.0	3.5	2.5	2.5	5.5	5.0	6.0	5.0	4.0	1.0	5.0	1.0	29.7	B
27	4.0	4.0	3.5	3.2	4.8	1.0	5.5	6.5	2.5	5.2	5.0	6.0	5.0	4.0	5.0	5.0	1.0	29.7	B
37	4.0	3.0	1.0	4.0	4.5	4.5	4.5	4.5	2.0	4.5	5.0	6.0	5.0	4.0	3.0	5.0	4.5	29.7	B
65	4.0	3.0	3.0	4.0	4.0	3.0	4.0	3.0	6.0	4.0	5.0	6.0	5.0	4.0	5.0	4.0	3.0	29.5	B
25	4.0	3.2	3.5	3.2	4.3	3.5	2.5	2.5	3.5	5.5	5.0	6.0	5.0	4.0	2.5	2.5	3.0	29.5	B
16	4.0	3.2	1.0	3.2	4.3	5.5	5.5	5.2	5.2	5.2	5.0	6.0	5.0	4.0	5.0	5.0	4.5	29.4	B
60	4.0	4.0	2.0	6.0	5.0	4.5	4.0	3.0	2.0	3.0	5.0	6.0	5.0	4.0	4.0	3.0	5.0	28.9	B
13	4.0	3.2	3.5	5.5	4.7	1.0	3.5	4.5	4.2	6.0	5.0	6.0	5.0	4.0	3.0	5.0	1.0	28.6	B
19	4.0	3.2	3.5	4.0	3.7	5.5	5.5	3.5	4.5	7.0	5.0	6.0	5.0	4.0	1.0	3.0	1.0	28.2	B
2	4.0	3.2	1.0	3.2	4.5	4.5	5.5	5.5	4.5	5.5	5.0	6.0	5.0	4.0	3.0	5.0	3.0	28.2	B
64	4.0	4.5	3.0	4.5	5.0	3.0	4.0	3.0	4.5	4.5	5.0	6.0	5.0	4.0	5.0	5.0	3.0	27.8	B
32	4.0	3.2	1.0	5.5	3.9	1.0	5.5	8.0	1.0	8.0	5.0	6.0	5.0	4.0	1.0	5.0	2.5	27.8	B
45	4.0	3.0	2.0	4.5	6.0	6.0	4.0	3.0	3.0	3.0	5.0	6.0	5.0	4.0	6.0	6.0	4.0	27.3	B
38	4.0	4.5	4.0	4.0	6.0	6.0	4.5	4.0	3.0	4.0	5.0	6.0	5.0	4.0	3.0	4.5	4.0	26.9	B
1	4.0	3.2	1.0	3.2	4.3	3.5	5.5	5.5	5.5	5.5	5.0	6.0	5.0	4.0	5.0	5.0	5.0	26.8	B
35	4.0	3.0	6.0	4.5	5.0	2.0	2.0	6.0	4.5	5.0	5.0	6.0	5.0	4.0	1.0	4.5	4.5	26.5	B
29	4.0	3.2	3.5	3.2	4.3	5.5	5.5	8.0	5.5	8.0	5.0	6.0	5.0	4.0	8.0	8.0	5.0	26.2	B
41	4.0	3.0	2.0	1.0	7.0	4.5	6.0	2.0	1.0	4.5	5.0	6.0	5.0	4.0	1.0	3.0	2.0	25.8	B
42	4.0	4.0	1.0	8.0	7.0	1.0	1.0	4.5	4.5	4.5	5.0	6.0	5.0	4.0	4.0	4.5	4.5	25.4	B
44	4.0	4.0	1.0	5.0	6.0	2.0	6.0	3.0	2.0	4.5	5.0	6.0	5.0	4.0	3.0	7.0	3.0	24.8	B
55	4.0	4.5	1.0	5.0	5.0	5.0	4.0	4.0	2.0	5.0	5.0	6.0	5.0	4.0	4.0	3.0	4.5	24.6	B
5	4.0	3.2	2.5	2.2	4.8	8.0	8.0	5.5	5.5	5.5	5.0	6.0	5.0	4.0	1.0	5.0	1.0	23.5	B
63	4.0	4.5	1.0	3.0	5.0	4.5	1.0	4.5	4.0	5.0	5.0	6.0	5.0	4.0	2.0	1.0	6.0	23.4	B
54	4.0	5.0	1.0	2.0	6.0	4.5	5.0	2.0	2.0	4.0	5.0	6.0	5.0	4.0	4.0	6.0	4.5	22.9	B
17	4.0	3.2	2.5	1.0	4.0	5.5	8.0	4.5	4.5	6.0	5.0	6.0	5.0	4.0	1.0	1.0	3.0	22.8	B
43	4.0	4.0	1.0	4.5	7.0	8.0	6.0	2.0	2.0	5.0	5.0	6.0	5.0	4.0	4.5	5.0	4.0	22.7	B
52	4.0	4.0	2.0	4.0	6.0	3.0	5.0	4.5	3.0	5.0	5.0	6.0	5.0	4.0	4.0	5.0	5.0	22.0	B
62	4.0	3.0	2.0	4.5	7.0	4.5	4.5	4.5	3.0	4.5	5.0	6.0	5.0	4.0	2.0	4.5	2.0	22.0	B
14	4.0	3.2	3.5	5.5	5.8	8.0	8.0	3.5	5.5	8.0	5.0	6.0	5.0	4.0	3.0	3.0	1.0	21.8	B
50	4.0	4.0	4.0	4.0	7.0	4.5	6.0	3.0	2.0	4.0	5.0	6.0	5.0	4.0	3.0	5.0	4.5	21.5	B
8	4.0	3.2	3.5	5.5	5.0	5.5	8.0	5.5	3.5	5.5	5.0	6.0	5.0	4.0	3.0	5.0	1.0	21.4	B
57	4.0	3.0	1.0	3.0	6.0	8.0	7.0	4.5	3.0	7.0	5.0	6.0	5.0	4.0	2.0	4.5	4.5	21.1	B
36	4.0	4.5	2.0	4.0	6.0	5.0	7.0	2.0	1.0	6.5	5.0	6.0	5.0	4.0	3.0	4.0	2.0	21.1	B
30	4.0	3.2	3.5	2.0	4.8	3.5	3.5	3.5	4.5	8.0	5.0	6.0	5.0	4.0	3.0	5.0	1.0	21.1	B
12	4.0	3.2	3.5	5.5	7.0	8.0	8.0	3.5	3.5	8.0	5.0	6.0	5.0	4.0	5.0	3.0	1.0	20.9	B
48	4.0	4.7	2.0	4.5	7.5	6.0	4.5	4.0	5.0	5.0	5.0	6.0	5.0	4.0	4.0	6.0	5.0	20.9	B
66	4.0	4.0	1.0	4.5	5.0	4.5	4.0	3.0	2.5	6.0	5.0	6.0	5.0	4.0	4.5	5.0	4.5	20.5	B
58	4.0	4.0	2.0	1.0	6.0	7.0	7.0	6.0	2.0	6.0	5.0	6.0	5.0	4.0	3.0	8.0	4.5	20.5	B
31	4.0	3.2	3.5	5.5	4.5	1.0	5.5	7.5	1.0	8.0	5.0	6.0	5.0	4.0	1.0	5.0	3.0	20.4	B
56	4.0	4.0	3.0	4.5	6.0	5.0	6.0	4.5	4.0	6.0	5.0	6.0	5.0	4.0	2.0	5.0	4.0	20.2	B
47	4.0	4.0	1.0	3.0	6.0	6.0	6.0	3.0	1.0	6.0	5.0	6.0	5.0	4.0	4.5	2.0	3.0	20.2	B
53	4.0	3.0	2.0	4.5	6.0	4.5	4.5	7.0	2.0	5.0	5.0	6.0	5.0	4.0	4.0	4.0	4.5	20.1	B
39	4.0	3.0	4.0	1.0	8.0	6.0	6.0	3.0	3.0	6.0	5.0	6.0	5.0	4.0	4.5	7.0	3.0	20.1	B
34	4.0	3.0	4.5	2.0	6.0	4.5	3.0	4.0	4.5	6.0	5.0	6.0	5.0	4.0	4.0	6.0	4.0	20.0	B
40	4.0	4.0	2.0	4.0	7.0	7.0	6.0	3.0	2.0	6.0	5.0	6.0	5.0	4.0	3.0	2.0	3.0	20.0	B
59	4.0	4.0	6.0	3.0	7.0	4.5	4.5	1.0	1.0	6.0	5.0	6.0	5.0	4.0	4.0	4.0	4.5	20.0	B
33	4.0	4.5	4.0	4.5	6.0	5.0	5.0	5.0	3.0	6.0	5.0	6.0	5.0	4.0	3.0	2.0	4.0	20.0	B
51	4.0	4.0	2.0	4.5	7.0	5.0	8.0	6.0	2.0	7.0	5.0	6.0	5.0	4.0	4.5	4.5	4.5	19.7	C
61	4.0	3.0	2.0	3.0	6.0	4.5	4.5	4.5	4.5	8.0	5.0	6.0	5.0	4.0	6.0	4.5	4.5	18.5	C
49	4.0	5.0	2.0	2.0	8.0	5.0	6.0	4.0	3.0	6.0	5.0	6.0	5.0	4.0	3.0	4.5	4.0	17.5	C

Note: v_1—Geological location; v_2—Roof design; v_3—Environmental conditions; v_4—Construction system; v_5—Preservation; r_6—Load state-modification; r_7—Live loads; r_8—Ventilation; r_9—Facilities; r_{10}—Fire; r_{11}—Inner environment; r_{12}—Precipitations; r_{13}—Temperature; r_{14}—Population growth; r_{15}—Heritage value; r_{16}—Furniture value; r_{17}—Occupancy.

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