

**Analysis of Natural Stone Wall Function Index Using Fuzzy Building Service Life (FBSL)**

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**Article History**

Received : February 19, 2026

Revised : February 28, 2026

Accepted : March 1, 2026

Published : March 1, 2026

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**Cite This Article:**

Velantika, G. J., Sari, A. F., Putri, K. M. E., & Widowati, E. D. (2026). Analysis of Natural Stone Wall Function Index Using Fuzzy Building Service Life (FBSL). *International Journal Science and Technology*, 5(1), 14–27.

**DOI:**

<https://doi.org/10.56127/ijst.v5i1.2612>

**Abstract:** Natural stone wall claddings are widely used in residential buildings, but their functional performance often declines earlier than the building's structural design life due to environmental exposure and installation-related deterioration. **Objective:** This study aims to quantify the functional condition of natural stone wall claddings using a Function Index (FI) so that maintenance decisions can be made more consistently and objectively. **Methodology:** A quantitative case-study approach was applied to five residential buildings in Situbondo Regency. Data were collected through field observations and building-age documentation, assessed using expert judgment, and analyzed using a fuzzy inference-based Fuzzy Building Service Life (FBSL) model to obtain a crisp FI score for each building. **Findings:** The results indicate that one building was classified as moderate/fair (FI = 56), while four buildings were classified as poor (FI = 0–23), implying higher maintenance urgency. When linked to the estimated Remaining Service Life (RSL) under an assumed 50-year design life and a 2020 observation year, an exploratory exponential relationship between FI and RSL was obtained ( $y = 12.177e^{0.3243x}$ ;  $R^2 = 0.7444$ ). **Implications:** The FI can serve as a practical decision-support indicator to prioritize immediate repair, scheduled maintenance, or routine monitoring for façade components, even when the building still has considerable remaining design life. **Originality:** This research contributes by integrating a fuzzy-based functional condition index for natural stone claddings with a remaining service life perspective in a residential case-study context, bridging qualitative inspection outcomes with interpretable maintenance planning.

**Keywords:** Building Service Life; Fuzzy Logic; Natural Stone; Function Index; Wall Cladding

**INTRODUCTION**

Natural stone cladding is widely used as an architectural wall finishing material in middle-class and upper-middle-class residential buildings because it offers distinctive textures, shapes, and color variations that enhance façade aesthetics. In many residential areas, including Situbondo Regency, natural stone is commonly applied not only to exterior walls but also to fences and boundary elements. However, field observations frequently indicate that natural stone installations experience physical deterioration such as surface scaling, discoloration, joint degradation, and adhesive weakening, which eventually require repair or replacement even when the structural components remain intact (Silva et al., 2013; Wasserman et al., 2023).

From a practical perspective, deterioration of façade materials affects not only visual performance but also maintenance planning and building usability. In residential contexts, maintenance decisions are often based on subjective assessments, resulting in inconsistent timing of interventions. Therefore, a structured approach that can translate observed conditions into measurable indicators is essential to support more reliable decision-making in building maintenance management ([Besiktepe et al., 2021](#); [Re Cecconi et al., 2019](#)).

Research on building envelope durability has extensively examined service-life prediction models to understand the degradation behavior of façade materials. Natural stone claddings, particularly those directly adhered to substrates, are known to exhibit shorter service life compared with other building components because their performance is strongly influenced by environmental exposure and workmanship quality ([Silva et al., 2011](#)). Subsequent studies have demonstrated that degradation processes of façade systems are multi-factorial and require systematic assessment frameworks to support lifecycle planning ([Silva et al., 2013](#); [Vieira et al., 2015](#)).

Another major body of literature distinguishes between physical service life and functional service life. Physical service life relates to material degradation, whereas functional service life reflects whether the component still meets user expectations and performance requirements. For façade elements such as natural stone, functional acceptability may decline before structural failure occurs, making functionality-based evaluation crucial for maintenance decision-making ([Prieto et al., 2016](#)). This perspective is consistent with broader building performance research that emphasizes the importance of functional indicators for evaluating serviceability and prioritizing maintenance interventions ([Dejaco et al., 2017](#); [Re Cecconi et al., 2019](#)).

In recent years, fuzzy logic has been widely adopted as a decision-support tool for building condition assessment because it can accommodate uncertainty and subjective judgments in inspection processes. By translating linguistic evaluations into quantitative outputs through membership functions and inference rules, fuzzy systems provide a systematic way to evaluate building performance under uncertain conditions ([Mamdani & Assilian, 1975](#); [Zadeh, 1965](#)). Applications in facility condition assessment demonstrate that fuzzy-based indices can improve consistency in maintenance prioritization and provide more interpretable results for decision-makers ([Besiktepe et al., 2021](#); [Marzouk & Awad, 2016](#)). Based on these considerations, this study applies a Fuzzy Building Service Life (FBSL) framework to evaluate the functional condition of natural stone walls in five

residential buildings located in Situbondo Regency. The objectives are to (1) determine the classification and level of deterioration using a functional condition index derived from fuzzy inference, and (2) compare the FBSL-based results with the remaining service life (RSL) of the observed natural stone walls. In this research, the Function Index (FI) is defined as the crisp output value generated after defuzzification, representing the quantified functional condition of the wall system (Prieto et al., 2016).

The central argument of this study is that a fuzzy-based modelling approach can provide a more consistent and reliable representation of functional building condition than deterministic scoring methods, particularly when inspection variables are expressed qualitatively and involve uncertainty. Accordingly, it is hypothesized that lower Function Index values indicate poorer functional condition and higher maintenance urgency, while higher Function Index values correspond to acceptable performance and longer remaining service life. Testing this relationship is expected to demonstrate the effectiveness of the FBSL framework as a decision-support tool for maintenance planning of natural stone cladding systems (Marzouk & Awad, 2016; Vieira et al., 2015).

## RESEARCH METHOD

This study was conducted on five simple residential buildings with natural stone walls in the Situbondo Regency. Data obtained from observations included the condition of the walls and the year of completion of the natural stone walls. Assessment of the condition of these buildings should involve expert judgment in order to produce a more accurate building condition index. The expert judgement has experience in building maintenance as well as structural assessment. The initial stage of scoring process is field observation that includes surface deterioration, cracking condition, and joint degradation. It follows the linguistic rating. Table 1 shows the basic data for the five buildings to be observed.

**Table 1.** Building data.

Code	Year Built	Capture	Service Life	Description
B1	2015		5	Natural stone wall used as architectural wall element of the house, with good condition and adequate lighting.

Code	Year Built	Capture	Service Life	Description
B2	2004		16	Natural stone wall used as a house fence, with condition beginning to deteriorate.
B3	2001		19	Natural stone wall used as a pool boundary wall, frequently exposed to water splashes from the pool.
B4	2001		19	Natural stone walls are used as an architectural wall element of the house, with condition beginning to deteriorate.
B5	1996		24	Natural stone walls are used as an architectural element of the house wall, with condition beginning to deteriorate.

The observation data will then be processed using fuzzy logic. The input data used in this study consists of six input factors, namely geographical location, environmental conditions, overload or excess load, indoor environment, rainfall, and temperature. These six factors are coded as follows: V1 is geographical location, V2 is environmental conditions, V3 is overload, V4 is indoor environment, V5 is rainfall, and V6 is temperature. The input values of the six factors are presented in Table 2. Each factor has a range of assessments that reflect the condition of the building. The assessments range from very good to poor. Each value also has a different value.

**Tabel 2.** Fuzzy values for the input parameters of the FBSL model.

Factor	Linguistic Code	Code	Range
V1	Very Good	SB	$1.0 < V < 1.5$
	Good	BK	$1.5 < V < 2.5$
	Moderate	SD	$2.5 < V < 3.5$
	Poor	BU	$3.5 < V < 4.0$
V2 - V6	Very Good	SB	$1.0 < V < 2.0$
	Good	BK	$2.0 < V < 4.5$
	Moderate	SD	$4.5 < V < 7.0$
	Poor	BU	$7.0 < V < 8.0$
Conclusion	Poor	BU	$0 < X < 46$
	Moderate	SD	$46 < X < 74$
	Good	BK	$74 < X < 100$

Table 3 describes the damage classification scheme based on the Function Index (FI), which represents the final output of the defuzzification process in the FBSL model. The FI values are divided into three condition levels Poor ( $0 - <46$ ), Moderate ( $46 - <74$ ), and Good ( $74 - 100$ ) each accompanied by a description of the functional condition of the natural stone walls and the corresponding recommended maintenance action. This classification provides a practical guideline for determining maintenance priorities, ranging from Immediate Repair for poor conditions to Routine Monitoring for acceptable conditions.

**Tabel 3.** Damage Classification

Function Index (FI)	Damage Level	Condition Description	Recommended Action
$0 - < 46$	Poor	Severee deterioration	Immediate Repair
$46 - < 74$	Moderate	Functional decline	Scheduled Maintenance
$74 - 100$	Good	Acceptable condition	Routine Monitoring

Table 2 describes the parameters that will be used in this study. Each parameter, except for the conclusion parameter, has four criteria. Parameter V1 (geographic location) has the same criteria but a separate scope because the parameters and criteria are written based on the journal by Prieto et al. (2016). Meanwhile, parameters V2 to V6 have the same criteria and the same scope. V1 (geographical location) is uniform coastal climate exposure. The assumed uniform design service life applies specifically to architectural natural stone wall elements and does not represent the primary structural system of the building. For V1 (geographical location), the excellent criterion is in the range of 1.0 to 1.5, the good criterion is in the range of 1.5 to 2.5, the moderate criterion is in the range of 2.5 to 3.5,

and the poor criterion is in the range of 3.5 to 4.0, with the respective codes being SB, BK, SD, and BU. Meanwhile, for parameters V2 to V6, the excellent criteria are in the range of 1.0 to 2.0, good criteria are in the range of 2.0 to 4.5, moderate criteria are in the range of 4.5 to 7.0, and poor criteria are in the range of 7.0 to 8.0. The conclusion parameter only has three criteria, with poor criteria in the range of 0 to 46, moderate criteria in the range of 46 to 74, and good criteria in the range of 74 to 100.

**Tabel 4.** Fuzzy logic input factors for each building.

Input Factor	Assessment Factor				
	B1	B2	B3	B4	B5
V1	1	1	1	1	1
V2	4	7,5	8	7	5
V3	1	1	1	1	1
V4	2,5	6	7,5	6	7,5
V5	5	5	5	5	5
V6	6	6	6	6	6

Table 4 shows the input factors that have been standardized based on their respective parameters. The assessment of input factors should involve expert judgment or people who are experts in their fields to assess a building condition in order to obtain more accurate data.

Table 4 shows that there are several variable values that are the same for each building. These variables are V1, V3, V5, and V6. This is due to the following considerations (Prieto et al., 2016):

1. V1 (geological conditions) has a value of 1 because all cases are located in the same area, namely Situbondo Regency, with the assumption that the location is very good.
2. V3 (overload) has the same value of 1 because it is assumed that there is no load on the walls since walls are non-structural parts of a building.
3. V5 (rain) has the same value of 5. This consideration was made because Situbondo Regency is close to the sea, so rainfall is quite low.
4. V6 (temperature) has the same value of 6. This consideration was made because Situbondo Regency has a relatively hot temperature ranging from 30 to 34 degrees Celsius and it rarely rains due to its location close to the sea.

After determining the factors or variables to be used, the next step is to determine the degree of membership function for each variable that has been determined. The next steps are described as follows:

a. Fuzzification

The fuzzification process in this study was carried out on six variables with membership described as follows:

1. Fuzzification V1

$$\mu_{SB} \left\{ \begin{array}{ll} 0 & ; \quad X \geq 1,5 \\ \frac{1,5 - X}{1,5 - 1} & ; \quad 1 < X < 1,5 \\ 0 & ; \quad X \leq 1 \end{array} \right.$$

$$\mu_B \left\{ \begin{array}{ll} 0 & ; \quad X \leq 1,5 \text{ or } X \geq 2,5 \\ \frac{X - 1}{1,5 - 1} & ; \quad 1 < X < 1,5 \\ \frac{2,5 - X}{2,5 - 2} & ; \quad 2 < X < 2,5 \\ 1 & ; \quad 1,5 \leq X \leq 2 \end{array} \right.$$

$$\mu_{SD} \left\{ \begin{array}{ll} 0 & ; \quad X \leq 2,5 \text{ or } X \geq 3,5 \\ \frac{X - 2}{2,5 - 2} & ; \quad 2 < X < 2,5 \\ \frac{3,5 - X}{3,5 - 3} & ; \quad 3 < X < 3,5 \\ 1 & ; \quad 2,5 \leq X \leq 3 \end{array} \right.$$

$$\mu_{BU} \left\{ \begin{array}{ll} 0 & ; \quad X \leq 3,5 \\ \frac{3,5 - X}{4 - 3,5} & ; \quad 3,5 < X < 4 \\ 0 & ; \quad X \geq 4 \end{array} \right.$$

2. Fuzzification V2 until V6

$$\mu_{SB} \left\{ \begin{array}{ll} 0 & ; \quad X \geq 2 \\ \frac{2 - X}{2 - 1} & ; \quad 1 < X < 2 \\ 0 & ; \quad X \leq 1 \end{array} \right.$$

$$\mu_B \left\{ \begin{array}{ll} 0 & ; \quad X \leq 2 \text{ or } X \geq 4,5 \\ \frac{X - 1}{2 - 1} & ; \quad 1 < X < 2 \end{array} \right.$$

$$\mu_{SD} \left\{ \begin{array}{ll} \frac{4,5 - X}{4,5 - 3} & ; \quad 3,5 < X < 4,5 \\ 1 & ; \quad 2 \leq X \leq 3,5 \\ 0 & ; \quad X \leq 4,5 \text{ or } X \geq 7 \\ \frac{X - 3,5}{4,5 - 3,5} & ; \quad 3,5 < X < 4,5 \\ \frac{7 - X}{7 - 6} & ; \quad 6 < X < 7 \\ 1 & ; \quad 4,5 \leq X \leq 6 \end{array} \right.$$

$$\mu_{BU} \left\{ \begin{array}{ll} 0 & ; \quad X \leq 7 \\ \frac{7 - X}{8 - 7} & ; \quad 6 < X < 8 \\ 0 & ; \quad X \geq 8 \end{array} \right.$$

3. Fuzzification Conclusion

$$\mu_{BU} \left\{ \begin{array}{ll} 0 & ; \quad X \geq 46 \\ \frac{46 - X}{46 - 1} & ; \quad 0 < X < 46 \\ 1 & ; \quad X \geq 0 \end{array} \right.$$

$$\mu_{SD} \left\{ \begin{array}{ll} 0 & ; \quad X \leq 46 \text{ or } X \geq 74 \\ \frac{46 - X}{74 - X} & ; \quad 38 < X < 46 \\ \frac{46 - 38}{74 - 46} & ; \quad 46 < X < 74 \\ 1 & ; \quad 46 \leq X \leq 74 \end{array} \right.$$

$$\mu_B \left\{ \begin{array}{ll} 0 & ; \quad X \leq 74 \\ \frac{X - 74}{100 - 74} & ; \quad 74 < X < 100 \\ 0 & ; \quad X \geq 100 \end{array} \right.$$

The degree of membership function of each variable is obtained from the function graph.

b. Basic Inference Rules

During the inference process, several rules are determined that will be used to generate conclusions. This study uses 16 rules to generate accurate conclusions. The rules used in this study are presented in Table 5.

**Table 5.** Inference rules.

No	V1	V2	V3	V4	V5	V6	Conclusion
1	Very Good	Very Good	Very Good	Very Good	Moderate	Moderate	Good

No	V1	V2	V3	V4	V5	V6	Conclusion
2	Very Good	Very Good	Very Good	Good	Moderate	Moderate	Good
3	Very Good	Very Good	Very Good	Moderate	Moderate	Moderate	Moderate
4	Very Good	Very Good	Very Good	Bad	Moderate	Moderate	Moderate
5	Very Good	Good	Very Good	Very Good	Moderate	Moderate	Good
6	Very Good	Good	Very Good	Good	Moderate	Moderate	Good
7	Very Good	Good	Very Good	Moderate	Moderate	Moderate	Moderate
8	Very Good	Good	Very Good	Bad	Moderate	Moderate	Moderate
9	Very Good	Moderate	Very Good	Very Good	Moderate	Moderate	Good
10	Very Good	Moderate	Very Good	Good	Moderate	Moderate	Moderate
11	Very Good	Moderate	Very Good	Moderate	Moderate	Moderate	Moderate
12	Very Good	Moderate	Very Good	Bad	Moderate	Moderate	Moderate
13	Very Good	Bad	Very Good	Very Good	Moderate	Moderate	Good
14	Very Good	Bad	Very Good	Good	Moderate	Moderate	Moderate
15	Very Good	Bad	Very Good	Moderate	Moderate	Moderate	Bad
16	Very Good	Bad	Very Good	Bad	Moderate	Moderate	Bad

Table 5 presents the inference rules that will be used to draw conclusions. An example of reading the inference rules in number 1 is if V1 (geographical location) is very good, V2 (environmental conditions) is very good, V3 (overload) is very good, V4 (internal environment) is very good, V5 (rain) is moderate, and V6 (temperature) is moderate, then the decision that will be made is good. Similarly, in number 2, if V1 (geographical location) is very good, V2 (environmental conditions) is very good, V3 (overload) is very good, V4 (internal environment) is good, V5 (rain) is moderate, and V6 (temperature) is moderate, then the decision that will be made is good. The readings apply to the subsequent sequences up to the last sequence in number 16.

The table also shows that there are similar conditions in all rules, namely V1 (geographical location) is very good, V3 (overload) is very good, V5 (rain) is moderate, and V6 (temperature) is moderate. These four factors are assessed as similar because they are in accordance with the previous explanation.

## RESULT

This study aimed to obtain information related to the functional condition and service-life implications of natural stone walls in five simple residential buildings in Situbondo Regency, East Java. The building functional condition was quantified using fuzzy logic through the Fuzzy Building Service Life (FBSL) framework. The analysis consisted of fuzzification, application of inference rules, and defuzzification to obtain a crisp output

value (Function Index/FBSL score) for each case. The calculated FBSL results are presented in Table 5.

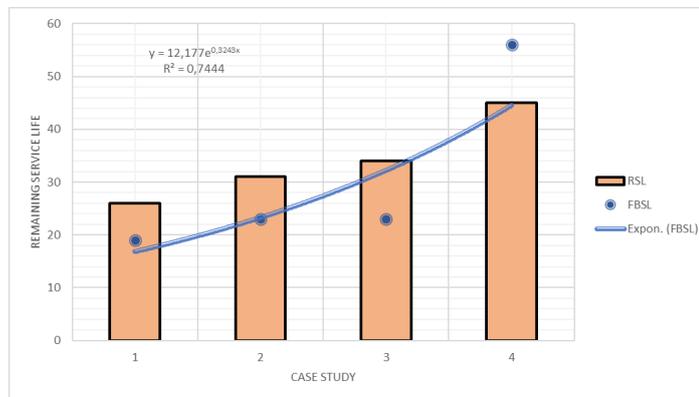
**Table 6.** Calculation Result of FBSL.

Building	FBSL
B1	56
B2	23
B3	23
B4	0
B5	19

Based on the classification in Table 3, Building B1 (FBSL = 56) falls into the Moderate condition category ( $46 < 74$ ). Buildings B2 and B3 (FBSL = 23) fall into the Poor condition category ( $0 < 46$ ). Building B4 (FBSL = 0) represents the lowest functional condition and is also classified as Poor. Building B5 (FBSL = 19) is likewise categorized as Poor.

To relate functional condition to remaining service life (RSL), service life was referenced to EN 1990 (basis of structural design), where typical design service-life categories include 10 years (temporary structures), 10–25 years (replaceable structural parts), 15–30 years (agricultural buildings), 50 years (general buildings), and 100 years (monumental/civil landmark structures). In this study, the overall service life was assumed to be 50 years for the residential buildings. Using the building year and the observation year (2020), the estimated remaining service life values were: B1 = 45 years, B2 = 34 years, B3 = 31 years, B4 = 31 years, and B5 = 26 years.

A relationship plot between RSL and FBSL was then developed (Figure 1). Building B4 was excluded from the curve fitting because its FBSL value was 0, indicating an immediate rehabilitation need. For the remaining four cases, the fitted exponential relationship was obtained as  $y = 12.177e^{0.3243x}$ , with  $R^2 = 0.7444$ .



**Figure 1.** Relationship between Remaining Service Life (RSL) and FBSL values of natural stone walls

## DISCUSSION

The results demonstrate that the Fuzzy Building Service Life (FBSL) model successfully differentiates the functional condition of natural stone wall claddings across the five observed residential buildings. Building B1, with an FBSL value of 56, falls into the moderate condition category, indicating that deterioration has begun but the wall system remains functionally serviceable. In contrast, Buildings B2, B3, B4, and B5 fall into the poor condition category, with FBSL values ranging from 0 to 23, suggesting that their functional performance has declined significantly and requires immediate maintenance intervention. When compared with the Remaining Service Life (RSL), it is evident that buildings with lower FBSL values tend to exhibit reduced functional serviceability despite still having considerable structural service life.

The variation in FBSL values among the buildings reflects differences in environmental exposure, maintenance history, and physical deterioration conditions. Building B1 shows moderate degradation because its natural stone cladding still maintains sufficient bonding and surface integrity, allowing it to remain functionally acceptable. Meanwhile, the low FBSL values observed in Buildings B2, B3, B4, and B5 are likely associated with visible defects such as joint deterioration, adhesive failure, and surface wear. These defects reduce the architectural and functional performance of the wall system even though the primary structural components may still be intact. This finding supports the concept that functional service life is influenced not only by physical deterioration but also by the level of serviceability perceived in the building envelope.

The findings align with previous studies on natural stone cladding performance, which highlight that façade components often experience functional decline earlier than their structural counterparts due to exposure-related degradation mechanisms. (Silva et al., 2011) demonstrated that environmental factors significantly influence the service life of natural stone claddings, while (Prieto et al., 2016) emphasized the importance of distinguishing between physical and functional service life when evaluating building components. Similar to the present study, (Vieira et al., 2015) showed that fuzzy-based modelling provides a practical method for translating qualitative inspection data into quantitative service-life indicators. The novelty of this research lies in integrating the FBSL-derived Function Index with Remaining Service Life analysis in a residential context, offering a combined functional–temporal perspective that is rarely addressed simultaneously in previous façade assessment studies.

The relationship between FBSL values and remaining service life suggests that functional deterioration of façade systems can serve as an early indicator of maintenance needs before structural end-of-life is reached. This implies that functional condition indices can play a critical role in preventive maintenance planning by identifying components that require intervention earlier than would be indicated by structural service-life estimates alone. In a broader context, this approach contributes to a more holistic understanding of building performance by incorporating both physical durability and functional usability into maintenance decision-making.

From a practical standpoint, the FBSL model demonstrates both strengths and limitations. Its strength lies in its ability to handle uncertainty and subjectivity inherent in visual inspections, producing a structured functional condition index. However, the model's predictive capability remains limited by the small number of case studies and the assumption of a uniform design service life for all buildings. Consequently, while the model effectively ranks maintenance priority among cases, further validation with larger datasets and varied environmental conditions is necessary to enhance its generalizability.

The findings suggest that implementing a fuzzy-based functional assessment approach can improve maintenance planning for residential building envelopes. Property owners and facility managers can use the Function Index as a decision-support tool to determine whether immediate repair, scheduled maintenance, or routine monitoring is required. From a policy perspective, incorporating functional condition indices into building inspection guidelines could support more systematic maintenance strategies, reduce premature replacement, and optimize resource allocation. Future research should focus on expanding the dataset, integrating additional environmental variables, and developing standardized inspection protocols to strengthen the application of FBSL in broader building asset management contexts.

## CONCLUSION

Modeling the service life of building components is complex and cannot be reliably represented by simple deterministic functions. The main lesson from this study is that the functional condition of natural stone wall claddings can deteriorate significantly even when a building still has substantial remaining design service life. Using the Fuzzy Building Service Life (FBSL) approach, Building B1 obtained a Function Index value of 56, indicating a moderate functional condition, while Buildings B2, B3, B4, and B5 recorded

values of 23, 23, 0, and 19, respectively, which fall within the poor condition category. These results indicate that most cases require immediate repair or rehabilitation to restore the functional and aesthetic performance of the cladding, whereas B1 can be managed through scheduled maintenance. Under the assumed design service life of 50 years and an observation year of 2020, the estimated remaining service life was 45 years for B1, 34 years for B2, 31 years for B3 and B4, and 26 years for B5. An indicative exponential relationship between remaining service life and FBSL was also obtained, expressed as  $y = 12.177e^{0.3243x}$  with  $R^2 = 0.7444$ .

This research contributes a practical application of a fuzzy inference framework for converting field observations into a single, interpretable functional condition score for natural stone wall claddings. By linking the FBSL-derived Function Index with remaining service life, the study provides an integrated perspective that combines functional performance assessment with temporal service-life considerations, offering a useful decision-support basis for maintenance prioritization of façade components in residential buildings.

However, the findings should be interpreted with caution due to several limitations. The study is based on a small number of case buildings, and the relationship between FBSL and remaining service life was derived from a limited dataset, which restricts statistical generalization. In addition, several input parameters were assumed to be uniform across buildings, and the remaining service life estimation relied on a general design service life assumption rather than component-specific degradation data. Future research should expand the number of case studies, incorporate more varied environmental exposure conditions, refine inspection and expert assessment procedures, and apply the method to other façade materials to enhance robustness and applicability.

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