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Impact of the Height of Buildings on the Maintainability of Natural Stone Claddings

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Abstract: The buildings' surroundings' environmental exposure conditions (e.g., orientation, location, altitude, distance from the sea, temperature, precipitation, presence of damp, exposure to prevailing winds, among others) have a considerable influence on the performance and durability of their envelope. Furthermore, the intensity of these conditions can vary significantly with the height of the building and, consequently, influence the degradation of different parts of the same building in different ways. In a tall building, the upper part is more prone to higher solar radiation levels, temperature variations, and exposure to wind–rain action. On the other hand, external elements at the bottom are more susceptible to high levels of pollution, especially in city centres. In this sense, the main purpose of this study was to analyse the degradation processes in buildings with different heights and understand whether the processes and maintenance requirements are statistically different. A sample of 203 natural stone claddings (NSC), located in Portugal, was used as case study. The sample was collected based on the diagnosis of the degradation condition of these claddings through in situ visual inspections. To predict the degradation process of NSC over time, a stochastic service life prediction model, based on Petri nets (PN), was implemented. This model allows evaluating the performance of NSC by encompassing the uncertainty of the future performance of the claddings. The results obtained through the degradation and maintenance models were compared with real case studies to highlight the real impact of buildings' height subjected to environmental exposure conditions on the maintainability of NSC.

Keywords: degradation; maintenance; environmental exposure conditions; tall buildings; natural stone claddings; Petri nets

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1. Introduction

The cladding materials, applied in façades and roofs, are the buildings' first protection level and, therefore, they are exceptionally vulnerable to the environment degradation agents and mechanisms [1]. Consequently, the surrounding environmental exposure conditions have a strong impact on the rate and severity of degradation of these materials [2]. The service life and maintenance needs of the different cladding solutions are influenced by factors such as location, orientation, altitude, distance from the sea, precipitation, temperature, presence of damp, and exposure to prevailing winds [3,4]. The service life of façade claddings is very variable, depending on the material applied, the exposure conditions, even the geographical context, and the consequent users' performance requirements [5,6]. In fact, the service life of the cladding materials varies around the world. For example, the Aon Center, in Chicago was initially clad in Italian Carrara marble, but the severe thermal cycles and environmental loads of Chicago led to early cracking and bowing of the marble slabs, and the building had to be re-cladded with white granite 15 years later [7–9]. Similar constructive solution presented different service lives in other places, for example 21 years in Helsinki (Finland), 25 years in Malmö (Sweden) and Paris (France), and 31 years in Nyköping (Sweden) [10,11]. The variation of the environmental exposure conditions with height can also considerably affect the rate and severity of the claddings' degradation. A study performed by Westberg et al. [12] reveals that tall buildings are more susceptible to weather effects. In the Aon Center, most of the cracked slabs were located on the elevated part of the building, subjected to higher sunlight exposure [13].

The environmental exposure conditions at the top and bottom of a tall building are distinct. The upper part of the building is less protected from these conditions, namely solar radiation, temperature variations, and the combined action of precipitation and prevailing winds [14,15]. On the other hand, the façades at the bottom of buildings are subjected to a higher level of pollution in the air [16]. The main purpose of this study is to understand whether the degradation process in tall buildings is statistically different from that in low buildings and assess the impact of these differences on the maintenance requirements. To assess the impact of the building's height on the degradation and maintenance conditions of natural stone claddings in external façades over time, a stochastic service life prediction model, based on Petri nets (PN), is implemented. This model allows evaluating the performance of NSC by encompassing the uncertainty of the future performance of the claddings [17]. The case study selected is composed of 203 natural stone claddings (NSC), 110 in low buildings and 93 in high-rise buildings, located in Portugal. The sample was collected based on the diagnosis of the degradation condition of these claddings through in situ visual inspections. In the methodology developed, the degradation process and three maintenance strategies are assessed: (i) total replacement only; (ii) combination of minor interventions and total replacement; and (iii) combination of cleaning operations, minor interventions, and total replacement.

To the authors' best knowledge, there are no studies in the literature that address this issue. First, the maintenance planning of claddings is not yet fully implemented in our society (the maintenance of this element is still seen as non-essential) [18,19]. Furthermore, when degradation models are used to predict the evolution of anomalies and plan the maintenance activities, it is assumed that the environmental exposure conditions are equal in all building [20,21]. Nowadays, from the literature, it is known that environmental exposure conditions have a considerable influence on the degradation process [22], especially the microclimate. Therefore, the analysis of the degradation process for different buildings' heights is fundamental to define adequate degradation curves to correctly model the claddings' behaviour. By reducing the uncertainties in the degradation process, better maintenance plans can be developed and, consequently, higher savings in the maintenance plan can be reached.

The outline of this paper is as follows: Section 2 provides a background of the variation of environmental exposure conditions according to the buildings' height; in Section 3, the material analysed and the maintenance model implemented are described; Sections 4 and 5 present the results obtained and their discussion, respectively; and, finally, the conclusions are drawn in Section 6.

2. Background: Variation of the Environmental Exposure Conditions According to Buildings' Height

The façades' durability is strongly influenced by the microclimate [23]. Local climate concerns the overall climate of the region and is related with the topography, rural or urban context, altitude, and distance to the sea of the building [3]. On the other hand, microclimate depends on the specific location and characteristic of the building, such as [12] orientation, materials, height, and surface protection (by elements existing in the façade or by external surrounding elements). Therefore, the assumption that environmental exposure conditions are constant along the height of a building is an over-simplistic approach.

Several studies show that existing environmental conditions are directly related with the buildings' height. Elshaer et al. [24] used different configurations of buildings (standalone and different surrounding heights) to assess the impact of wind loads on tall buildings. The authors concluded that the mean pressure magnitudes of the wind are higher on the top of the building and increase with height. However, the surrounding buildings have a protective effect, mainly at the bottom of the building, since the mean pressure magnitudes of the wind decreases with the increase in height of the surrounding buildings. On the other hand, the increase in height of the surrounding buildings contributes to the turbulence induced by the incoming wind. The risk of turbulence is considerably high at the bottom of the building when the height of the surrounding buildings is, approximately, 75% of the height of the building under analysis.

The pollutant concentrations are also higher at street level [16]. Azimi et al. [25], in Chicago, and Makhelouf [26], in Paris, analysed the vertical distribution of pollution around high-rises. In both studies, the measurements carried out show considerable differences in the pollutant concentrations as a function of floor elevation. These concentrations are more significant at the bottom of the building mainly because of traffic density. Only the ozone concentration increases with the height of the building [25,27]. From previous studies, it is possible to understand that pollutants related to road traffic are severely harmful to outdoor surfaces due to the dry deposition process [28,29].

Wind-driven rain intensity is another important parameter in the degradation of the buildings' envelope elements. The wind-driven rain has an active role in the deposition of atmospheric pollutants on building façades [30]. Ge et al. [31], from field measurements of wind-driven rain on mid- and high-rise buildings, and Blocken et al. [30], from numerical models, observed that the wind-driven rain intensity increases as a function of floor elevation, reaching its maximum at the roof of the buildings. Furthermore, when the rain is acid, the impact in the degradation is higher, since the buildings' elements are exposed to acid environments for a long time [29,32].

Regarding temperature, although the results of Azimi et al. [25] show that temperature decreases with height, Charisi et al. [33] found that the more exposed parts of buildings present high surface temperatures due to the high radiative flux that the building façades are exposed to and, consequently, a higher temperature variation along the day. In the context of degradation of buildings' envelope elements, higher temperature variations are more harmful than a high stable temperature [34]. Since the top of the building is more exposed, the impact of temperature variations is more visible in these areas. Furthermore, the top of the building is also more prone to higher indices of UV radiation [35]. Solar exposure has a considerable importance in the aging of building materials [36,37].

3. Materials and Methods

To assess the impact of the building's height on the degradation and maintenance conditions of façades, 203 natural stone claddings were selected as case studies. For that purpose, a stochastic service life prediction model, based on PN [17], was implemented. A condition-based maintenance model means that inspections are an important activity in the maintenance planning. In other words, planning the maintenance activities to be carried out is possible only after the assessment of the NSC condition through an inspection.

A stochastic service life prediction model is used to the detriment of well-established models, such as the factorial method [38]. Although the factorial method is flexible and relatively easy to apply, this deterministic method is extremely sensitive to small changes in the sub-factors' quantification. As more durability sub-factors are adopted, the complexity of the method increases, and the reference service life becomes more difficult to establish in an objective way [39]. The implementation of PN overcomes these limitations. The graphical representation allows describing the problem in a more intuitive manner; it is more flexible, since it allows incorporating more rules in the model to accurately simulate more complex problems and, at the same time, keep the model size within manageable limits. Probabilistic distribution can also be used to describe the degradation phenomena, providing more relevant information regarding the risk of failure of the claddings.

The research methodology implemented is divided into three main steps (Figure 1). In the step 1, a statistical analysis of the database is carried out, where the differences of weighted area of the façade affected by visual, loss of integrity, and loss of adhesion anomalies, according to the building's height, are identified. In step 2, the optimal parameters of the degradation model for high and low buildings are estimated for different probabilistic distributions. The exponential distribution is used to validate the degradation model. After that, the best probabilistic distribution is chosen, and the degradation curves are estimated. Finally, in step 3, the impact of maintenance activities is analysed, and values of high and low buildings are compared with the values of the complete sample.

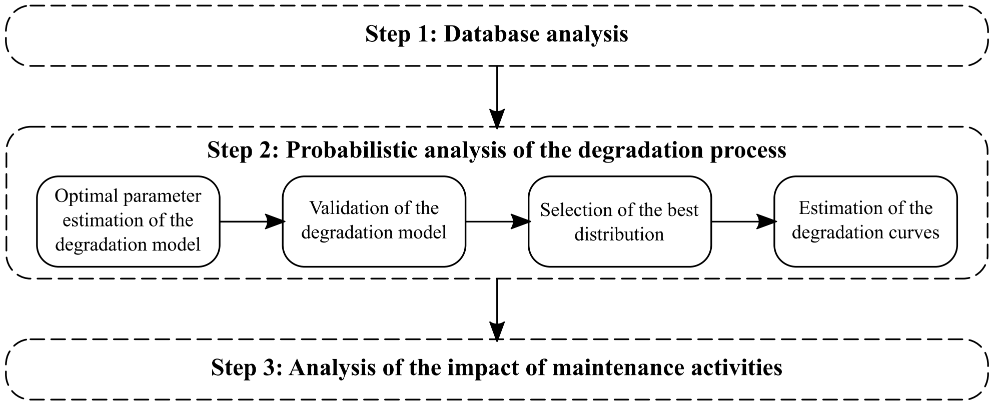

Figure 1. Diagram of the methodology implemented in this study.

3.1. Natural Stone Cladding

Over the years, several problems in natural stone claddings have been reported [11,40,41], derived mainly from inappropriate design, construction errors, and/or lack of maintenance [42,43]. The failure of NSC is extremely serious. The detachment of a stone element from the façade represents a high hazard to pedestrians and users [11,41,44]. Due to its unique appearance, natural stone provides an image of prestige and prosperity and is used as a cladding material in several buildings around the world, most of which are considered tall buildings. The knowledge of its behaviour and requirements is essential.

The database used in this study is composed of 203 NSC. A total of 54% of database elements correspond to low buildings (buildings up to five storeys) and 46% to high buildings (with more than five floors). The degradation condition of each NSC in the database was analysed based on in situ visual inspections.

The inspected buildings were randomly chosen. Buildings with different environmental exposures, locations, ages, heights, types of use, and types of stone were selected. The objective was to obtain a heterogeneous database. In terms of the type of stone, 35% of the database elements correspond to limestone, 27% to granite, and 38% to marble.

3.2. Classification System

The classification system to assess and characterise the degradation condition of buildings' claddings has been addressed by different authors [45–47]. In this study, a discrete classification system with five degradation conditions is used to assess the overall condition of NSC. This classification system was introduced by Silva et al. [39]. The overall degradation condition is determined through the severity of degradation index, S_w. Based on a visual assessment, the extent of the cladding affected by the different anomalies is recorded. The severity of degradation index is estimated by the ratio between the area affected by the anomalies observed in a NSC, weighted according to their severity, and a reference area equivalent to the total cladding area with the highest possible degradation condition (Equation (1)) :

$$S_w = \frac{\sum(A_n \times k_n \times k_{a,n})}{A \times \sum k_{max}}, \tag{1}$$

where k_n is the multiplying factor of anomaly n, as a function of its degradation condition (varying between 0 and 4); $k_{a,n}$ a weighting factor corresponding to the relative weight of the anomaly detected ($k_{a,n} \in \mathrm{R}^+$); A_n the area of cladding affected by an anomaly n (in m^2); A the façade's area (in m^2); $\sum k_{max}$ the sum of the multiplying factors for the highest degradation condition of each anomaly type. The severity of degradation index, S_w, ranges between 0 and 100%. The anomalies, the weighting factors (k_n and $k_{a,n}$), and more details about the classification system can be consulted in Silva et al. [39].

Figure 2 illustrates the relationship between the severity of degradation, S_w, and the degradation condition, C, with some examples. Condition A ($S_w \leq 1\%$) represents a NSC with no visible degradation; in condition B ($1 < S_w \leq 8\%$), the NSC begins to present some visual anomalies (superficial dirt and stains) and some signs of loss of integrity (material degradation and cracking); condition C ($8 < S_w \leq 20\%$) corresponds to a NSC with slight degradation, with anomalies related to joints and substrate degradation and loss of integrity (open joint, scaling of the edges, and fracture); condition D ($20 < S_w \leq 45\%$) corresponds to a NSC with moderate degradation (there is an evolution on the condition C anomalies); and condition E ($S_w > 45\%$) represents a NSC with generalised degradation and severe defects.

(**a**) (**b**) (**c**) (**d**)

Figure 2. General appearance of NSC in the different degradation conditions: (**a**) condition A ($S_w \leq 1\%$); (**b**) condition B ($1 < S_w \leq 8\%$); (**c**) condition C ($8 < S_w \leq 20\%$); (**d**) condition D ($20 < S_w \leq 45\%$). No example is provided for condition E because there is no NSC in this condition in the database.

3.3. Maintenance Model

Beyond the degradation process, the maintenance model adopted also includes the inspection and maintenance processes. Since it is a stochastic model, the uncertainties that arise from the inspection records, from the natural variability of the degradation process, and from the efficiency/impact of the maintenance actions are considered. Therefore, to consider the propagation of uncertainties during a building's lifetime, in this model, a Monte Carlo simulation is used (the sample size considered is 50,000). More details about the maintenance model can be found in Ferreira et al. [17].

3.3.1. Degradation Process

To adjust the maintenance model to model NSC in low- and high-rise buildings, the estimation of the firing rates of the transitions of the degradation process from the database is a fundamental step. For that purpose, several probability distributions are analysed. The probability distribution that best describes the degradation process of the NSC is the one that minimises the differences between the predicted and observed data. The fit of the probability distribution parameters to the database is carried out through the maximum likelihood method [48]. The log likelihood, log L, measures the difference between the observed data and those estimated by the model (Equation (2)).

$$\log L = \sum \log p_{ij}, \tag{2}$$

The log likelihood is given by the summation of the logarithm of the probability of transition from degradation i to j, p_{ij}, of all observed transitions presented in the database.

3.3.2. Impact of the Maintenance Activities

The database is also used to estimate the impact that a maintenance activity has on the NSC. The impact of a maintenance activity is quantified by assessing the effect this activity has on the severity of degradation index, S_w [49]. The impact of maintenance activities on the removal or repair of the anomalies observed is defined based on the literature or expert judgement. These values are used to perform a theoretical correction of the anomalies in the different records presented in the database. After theoretical analysis, a new severity of degradation index is estimated and, consequently, a new degradation condition. By comparing these records with the original, the probability that a NSC improves its condition is estimated.

In this study, only three types of intervention are considered in the maintenance model: cleaning operations, minor interventions, and total replacement. Cleaning operations are applied to remove part of the aesthetical and visual defects (e.g., surface dirt, stains, and efflorescence) and reduce microbiological growth. Minor intervention is a more detailed action than cleaning operations. Besides covering cleaning operations, it also considers localised repair and/or partial replacement of the NSC due to cracks or local loss of adhesion. Finally, in the last level, the whole cladding is replaced. In terms of implementation, it is assumed that a cleaning operation is required when a cladding presents a condition B of degradation, a minor intervention when the degradation condition is C, and a total replacement when condition is D or E.

For NSC, the fixed costs (at year 0), the application zones, and the impacts of the various types of interventions are presented in Table 1. More specifically, these values mean, for example, that a cleaning operation in NSC has a cost of EUR 31.37/m^2, is applied in condition B, and improves the NSC's condition to A with a probability of 15%, leading to no significant improvement with a probability of 85%. The costs were adapted from the literature [50].

Table 1. Fixed costs, application zones, and impacts of the different maintenance activities.

Interventions	Cost (EUR/m^2)	Application Zone	Impact of the Maintenance Activity (%)		
			P_A	P_B	P_C
Inspections	1.03	All	-	-	-
Cleaning operations	31.37	B	15.0	85.0	-
Minor interventions	68.80	C	0.0	80.4	19.6
Total replacement	149.51	D, E	100.0	-	-

3.3.3. Output of the Maintenance Model

The output of the maintenance model is given in terms of four parameters: service life, maintenance costs, efficiency index, and number of interventions over the time horizon.

Based on the literature, in this study, condition D defines the expected end of the service life (ESL) for NSC [39]. In the maintenance model, it is assumed that the ESL is reached when the probability of transition between conditions C and D is equal to 50% [23]. The maintenance costs correspond to the accumulated costs required, over the time horizon, t_h, to keep the NSC in operation (Equation (3)). These costs consider the costs related with inspections, $C_{inspection}$, and the other maintenance activities, $C_{maintenance}$. To consider future costs, a real discount rate, v, of 6% is considered [23].

$$C_{total} = \sum \frac{C_{inspection}}{(1+v)^t} + \sum \frac{C_{maintenance}}{(1+v)^t}, \tag{3}$$

The ability of maintenance strategy to maintain the NSC in a good condition is measured through the efficiency index (EI) (Equation (4)). The EI ranges between 0 and 1, and it is computed by the ratio between the area below the degradation curve with loss of performance, $\int S_w(t)\, dt$, and the area below the degradation curve when there is no degradation, $100 \cdot t_h$. The higher the *EI* value, the more efficient the maintenance strategy is over time [51].

$$EI = \frac{\int S_w(t)\, dt}{100 \times t_h}, \tag{4}$$

Finally, the number of total replacements corresponds to the average number of times that the cladding is totally replaced during the time horizon.

4. Results

In this study, the influence of the buildings' height on the degradation and maintenance of NSC is analysed. A time horizon of 150 years is considered in the several analyses performed. Furthermore, it is assumed that the NSC is in condition A at the beginning of the analysis (no visible degradation).

4.1. Degradation Condition of NSC According to the Façade's Height and the Environmental Exposure Conditions

As described in Equation (1), the severity of degradation index (and, consequently, the degradation condition) is estimated considering the area affected by the anomalies observed in a NSC.

Figure 3 shows the statistical analysis of the weighted area of the façade affected by visual anomalies according to the buildings' height. The main visual anomalies observed in the sample are colour change, damp stains, biological colonisation, and deposition of dirt or efflorescence (Figure 4). The results reveal that high buildings present higher areas affected by stains and by the deposition of biological agents. According to Neto and de Brito [52], these anomalies are mainly caused by wet–dry cycles and the action of water, by the presence of living organisms, and particles accumulation, higher buildings being more prone to this type of anomalies, as indicated by the sample.

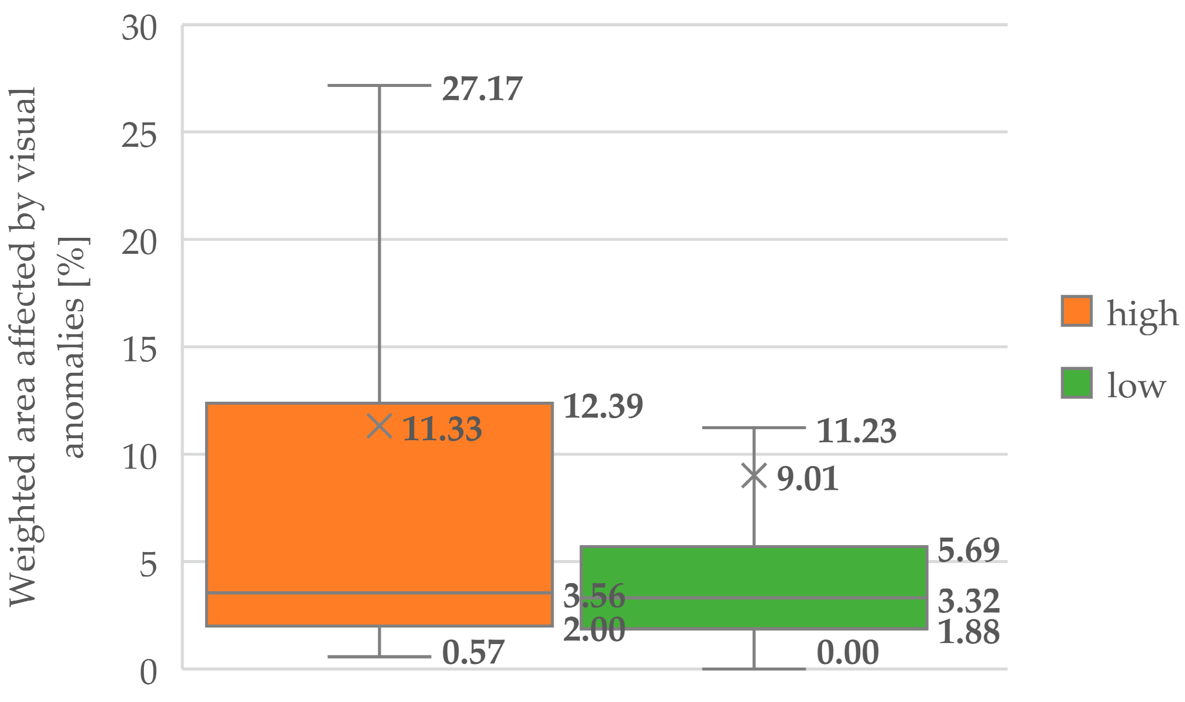

Figure 3. Boxplots of the weighted area of the façade affected by visual anomalies according to the buildings' height.

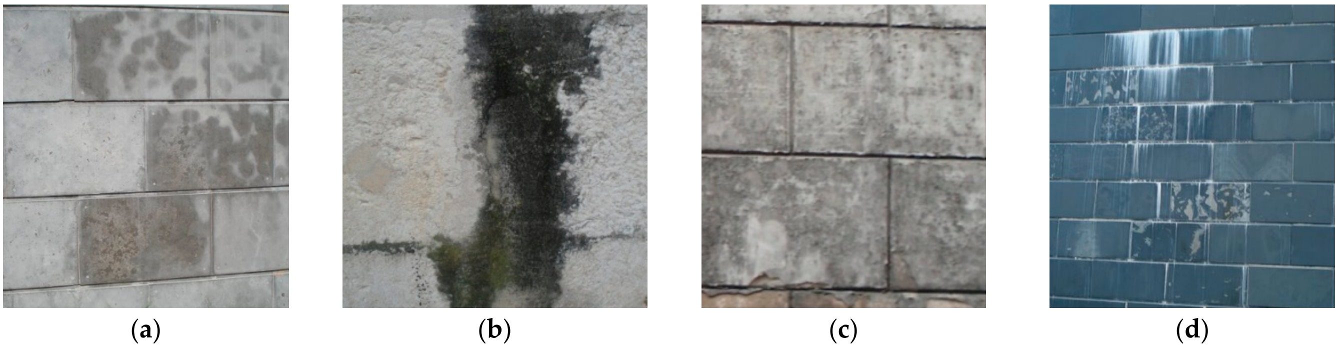

Figure 4. Illustrative examples of the visual anomalies observed in NSC: (**a**) damp stains; (**b**) biological colonisation; (**c**) dirt deposition; (**d**) efflorescence.

Concerning the anomalies related to the loss of integrity of NSC (loss, volume change, or degradation of the stone elements), the results reveal that these anomalies occur with a higher frequency in low buildings (Figures 5 and 6). These anomalies tend to be caused by chemical and biological actions, and the higher concentration of pollutants in the low buildings may justify these results [16]. On the other hand, physical actions, as impacts, and human actions can also promote these anomalies, and the lower parts of buildings are thus more susceptible to these actions.

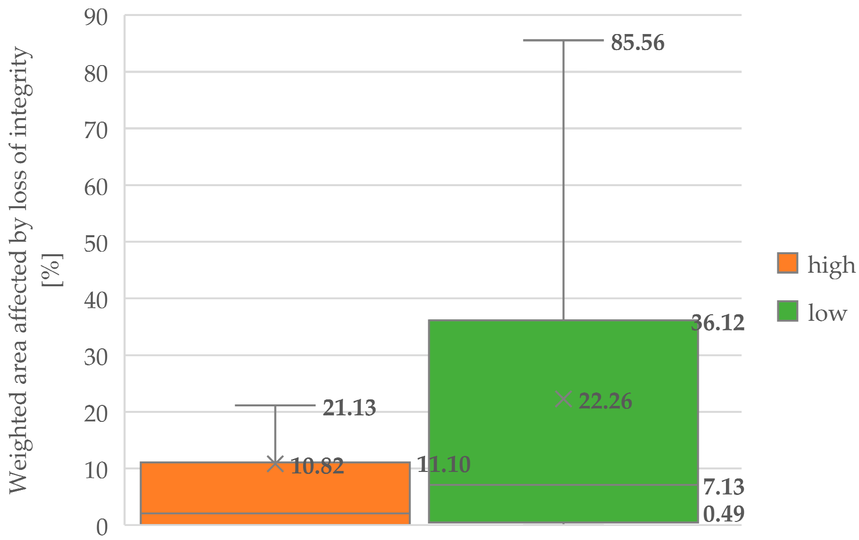

Figure 5. Boxplots of the weighted area of the façade affected by loss of integrity according to the buildings' height.

Figure 6. Illustrative examples of the loss of integrity anomalies observed in NSC located at the bottom wall of NSC façades.

Figure 7 presents a statistical analysis of the loss of adhesion anomalies according to the buildings' height and exposure to wind–rain action. For severe conditions of the combined action of wind and rain, high-rise buildings present higher areas affected by detachment, mainly due to the action of wet–dry cycles and thermal shocks. On the other hand, for a moderate exposure to wind–rain action, low buildings present higher areas affected by loss of adhesion anomalies. In this situation, these anomalies are mainly caused by other effects, such as excessive deformation of the substrate and structural-related movements of the walls, which are not directly related to the buildings' height.

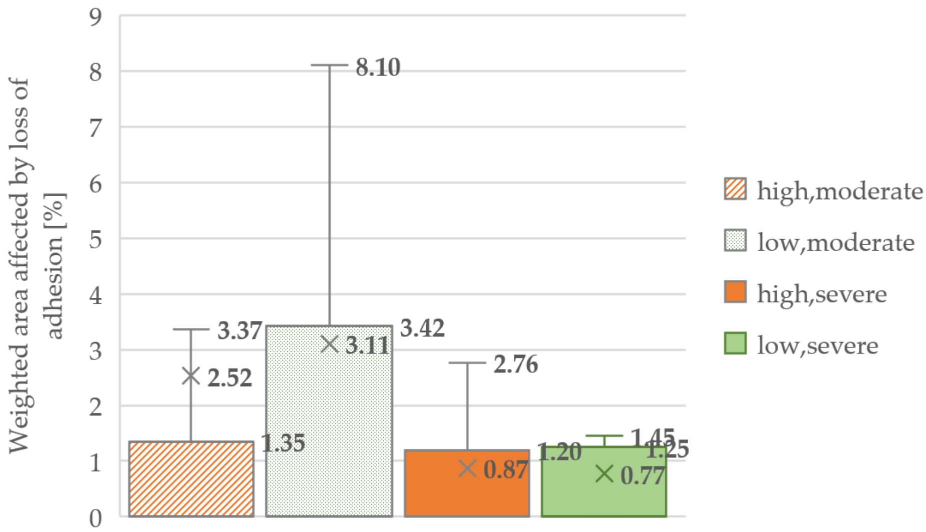

Figure 7. Boxplots of the weighted area of the façade affected by loss of adhesion anomalies according to the buildings' height and exposure to wind–rain action.

4.2. Probabilistic Analysis of the Degradation Process

To select the best probability distribution that describes the behaviour of the observed data, three probability distribution are analysed: exponential, Weibull, and lognormal. In addition, the parameters of the degradation process are also estimated through the Markov chains. Due to their wide application to model degradation processes [39,53–55], Markov chains are used to validate the degradation process in the Petri net maintenance model. In Table 2, the optimal parameters and the log likelihood value obtained for low and high buildings are compared, in terms of mean, T_i, and standard deviation, SD_i, of the permanence time in each degradation condition, with i = {A, B, C, D}.

Table 2. Comparison of the optimal parameters obtained for Markov chains and Petri net (exponential, Weibull, and lognormal) for low and high buildings.

Parameters		Low Buildings				High Buildings			
		Markov Chains	Exponential	Weibull	Lognormal	Markov Chains	Exponential	Weibull	Lognormal
Mean value (years)	T_A	5.4	5.6	4.6	4.9	6.0	5.0	4.2	6.5×10^3
	T_B	36.5	37.4	39.5	38.7	96.1	100.4	44.9	48.4
	T_C	81.7	77.1	26.2	29.0	111.1	129.8	16.8	18.6
	T_D	111.1	1.4×10^4	57.7	7.8×10^6	111.1	3.4×10^7	35.6	1.8×10^7
Standard deviation (years)	SD_A	5.4	5.6	4.4	5.8	6.0	5.0	19.5	9.3×10^{10}
	SD_B	36.5	37.4	12.4	14.5	96.1	100.4	7.5	11.6
	SD_C	81.7	77.1	2.1	0.9	111.1	129.8	0.6	0.4
	SD_D	111.1	1.4×10^4	3.2	4.9×10^7	111.1	3.36×10^7	1.8	1.4×10^8
$-\log L$		95.06	90.48	75.98	77.09	63.80	63.26	45.47	44.15

The validation of the degradation process in the Petri net maintenance model is carried out through the comparison exponential distribution and Markov chains results. For both heights, the values of the optimal parameters obtained through these two methodologies, for degradation conditions A, B, and C, are similar (Table 2). However, the differences observed in degradation condition D are already quite significant. The reason for this difference is related to a limitation of the database: it has no records in degradation condition E. The differences in the remaining degradation conditions occur due to sampling errors associated with the Monte Carlo simulation implemented in the Petri net degradation model. The above results can be confirmed in Figure 8. This figure presents the average degradation curves obtained for both methodologies and for heights. The curves are practically overlapped in degradation conditions A and B. In condition C ($8 < S_w \leq 20\%$), it is already possible to observe slight differences between the curves; but the differences from condition D ($20 < S_w \leq 45\%$) begin to be more pronounced. However, since it is assumed that the end of the service life is reached when the NSC reaches condition D, and there are no elements in condition E, it is considered that Petri Nets are adequate to describe the degradation process for both heights.

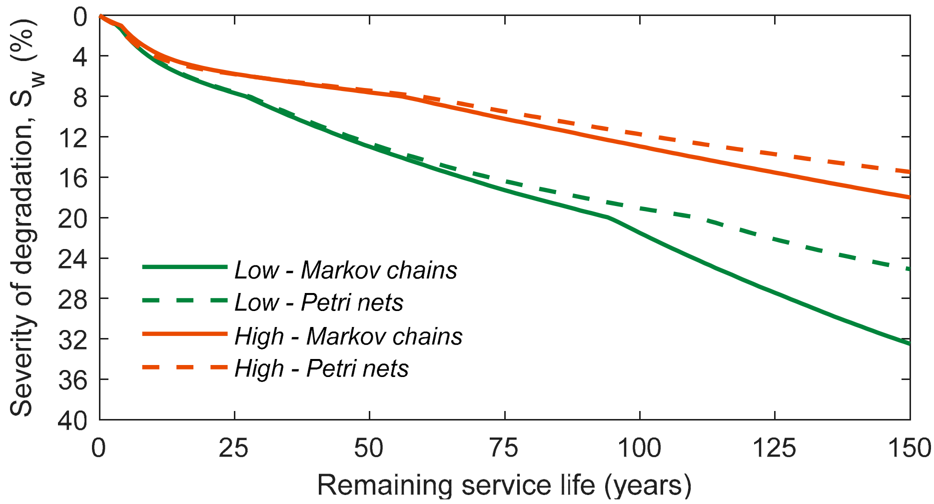

Figure 8. Comparison of the average degradation curves obtained for both models and heights.

After validation, the three probability distributions (exponential, Weibull, and lognormal) are compared to identify the distribution most suitable to describe the degradation process. By comparing the log likelihood values (Table 2), the results reveal that Weibull and lognormal distributions have a better fit to the historical data. These two probability distributions present the lowest log likelihood values for both heights. However, by analysing the optimal parameters, it is found that lognormal distribution has difficulties in modelling the permanence time in condition D for low buildings and in condition A and D for high buildings (Table 2). The values estimated are unrealistic. Therefore, based on these results, the Weibull distribution is selected as the more adequate distribution to describe the degradation process for both heights. In Figure 9, the average degradation curves obtained for the three probabilistic distributions and for both heights are compared. In this figure, the adequate fit of the Weibull distribution can be confirmed. According to the exponential and lognormal degradation curves, after 150 years, the severity of degradation index of the NSC is above 40% (i.e., condition E has not yet been reached). Since maintenance is not yet considered in the degradation curves, these two probability distributions reveal to be inadequate to describe the degradation process of NSC.

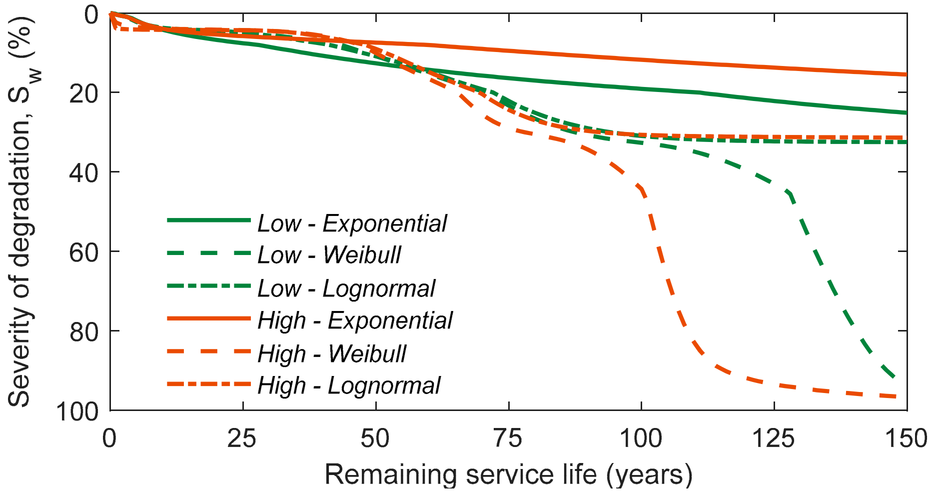

Figure 9. Comparison of the average degradation curves obtained for the three probabilistic distributions and for both heights.

Figure 10 presents the cumulative distribution functions (CDF) of the five degradation conditions for both heights computed with the Weibull distribution. The CDF allows evaluating the probability of the NSC moving from one condition to the next, the expected end of service life, and the permanence time of the NSC in each degradation condition. The ESL is identified in Figure 10 for both heights. For low buildings, an average service life of 71 years is obtained, and for high-rise buildings, that value is 65 years.

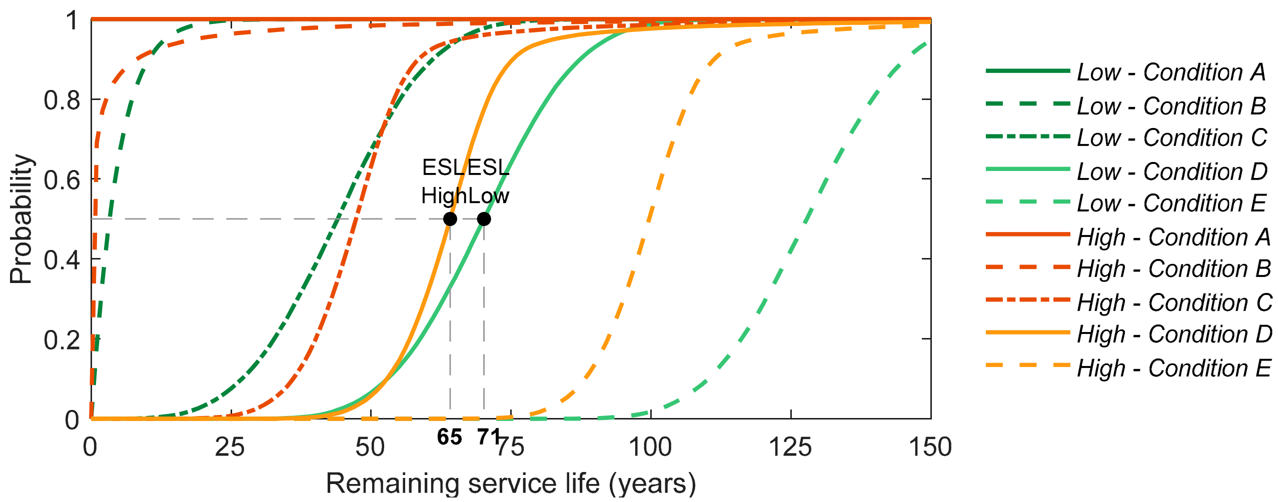

Figure 10. Cumulative distribution functions of the five degradation conditions over time horizon for both heights.

4.3. Comparison of the Different Maintenance Strategies

To introduce the impact of maintenance actions in low- and high-rise buildings, three maintenance strategies are analysed: (i) total replacement only; (ii) combination of minor interventions and total replacement; and (iii) combination of cleaning operations, minor interventions, and total replacement. These three maintenance strategies were defined based on previous works and on expert judgement [17,23,51]. For both heights, a periodicity between inspections of 5 years is considered.

In Figures 11 and 12, and Table 3, for both heights, the different parameters estimated for each maintenance strategy are compared. Furthermore, these results are compared with the values obtained for the complete sample of NSC. More details about the results of the complete sample can be found in Ferreira et al. [23,51].

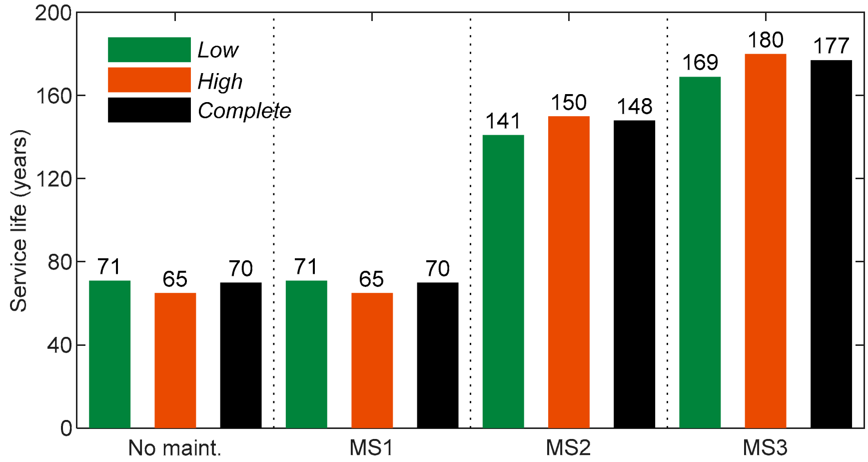

Figure 11. Comparison of the service life for both heights and for the complete sample.

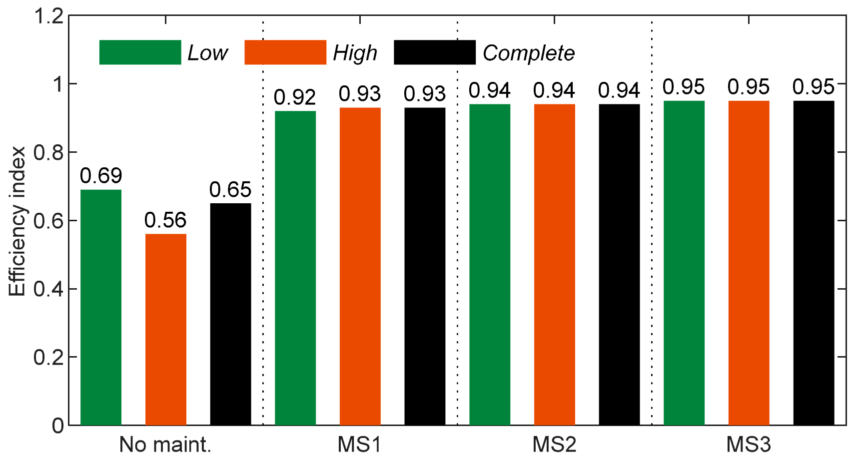

Figure 12. Comparison of the efficiency index for both heights and for the complete sample.

Table 3. Comparison of the total number of replacements and maintenance costs for both heights and for the complete sample.

Maintenance Strategy	Case Study	Maintenance Activity			Cost (EUR/m^2)
		Cleaning Operation	Minor Intervention	Total Replacement	
MS1	Low	-	-	1.7	6.01
	High	-	-	1.9	6.67
	Complete	-	-	1.7	5.98
MS2	Low	-	2.2	0.6	10.73
	High	-	2.1	0.5	8.40
	Complete	-	2.1	0.5	9.10
MS3	Low	5.7	2.0	0.3	45.85
	High	5.6	2.0	0.3	45.04
	Complete	5.6	2.0	0.3	44.65

Figure 11 compares the results of service life. In a simple way, they reveal that using preventive maintenance activities, such as cleaning operations and minor interventions, contributes to increasing the service life of NSC. These results are visible for both heights and in the complete sample. For the situations with maintenance (MS1, MS2, and MS3) and for the situation with no maintenance, the ESL ends when condition D is achieved. However, in MS1, MS2, and MS3, when condition D is achieved, the NSC is completely replaced, while in the situation with no maintenance, the NSC continues to degrade. This is the reason why the service lives obtained for MS1 and for the situation with no maintenance are the same. Since MS1 only includes total maintenance, the NSC degrades continuously until condition D without any maintenance being performed. The same behaviour can be observed for the situation with no maintenance. The difference between both situations is that in MS1, a total replacement is carried out when the degradation condition is D, while in situation with no maintenance, maintenance activities are not carried out.

Furthermore, as maintenance strategies become more complex (from MS1 to MS3), along with the increase in service life, the efficiency index also increases (Figure 12). This observation is valid for both heights and for the complete sample. This result means that using preventive maintenance activities increases the probability of the NSC remaining in the most favourable degradation conditions (such as conditions A and B) for longer. Consequently, the aesthetic appearance of the NSC is better during the time horizon.

On the other hand, the increase in complexity of the maintenance strategy translates into an increase in the global number of interventions and maintenance costs (Table 3), as expected. However, by closely analysing Table 3, it is found that, although the global number of interventions increased, the number of replacements was substantially reduced. This result is relevant because the replacement of all NSC is the most time-consuming maintenance activity, and reducing that number over the time horizon allows increasing the users' satisfaction. Regarding costs, there is a close relationship with the number of interventions, i.e., the increase in the number of interventions has a greater impact on the maintenance costs.

5. Discussion

Through a simple analysis of the results obtained with no maintenance, it is found that they are coherent with the studies in the literature [12,39]. By comparing the service life of NSC (Figure 10) for both heights, the results reveal that NSCs are more durable in short buildings than in tall buildings. These results show the environmental loads that tall buildings are subjected to (such as higher temperature [33], wind-driven rain intensity [30], and wind loads [24]) contribute to accelerating the degradation process of NSC.

From the results considering maintenance (Figures 11 and 12, and Table 3), it is understood that the characteristics of NSC's maintenance continue to depend on height. By starting the analysis with MS1 results, in general, the parameters estimated through the complete sample can be used to describe the behaviour in low buildings. However, the differences between the complete sample and the sample of the high-rise buildings are more significant but expected. High-rise buildings have a lower service life. Consequently, compared to low buildings, the maintenance activities of total replacement will occur sooner. Over time, this implies that the number of interventions and the maintenance cost will be higher. In terms of the efficiency index, since the values are very close, the only possible conclusion to draw is that the efficiency of MS1 is similar for both heights, although the impact of the maintenance activities is higher for higher buildings.

The results of MS2 may seem a little counter intuitive. They reveal that the service life for high-rise buildings is longer than for low buildings. This result is justified by the permanence time in condition B, T_B (Table 2). MS2 includes minor interventions and total replacement activities. Minor interventions have condition C as trigger, while for total replacement, it is condition D and E. Table 2 shows that the permanence time in the most favourable conditions (A and B) for high buildings is, approximately, 5 years longer. Consequently, minor interventions will occur earlier in low buildings, which implies a slightly higher number of interventions and maintenance costs. Another reason is the fact that the impact of minor interventions is the same for both heights (Table 1). Therefore, since they allow postponing the total replacement of the NSC for longer periods, minor interventions are more efficient in high-rise buildings. In terms of efficiency index, the values are again similar for both heights. For MS3, similar observations can be made. Finally, for MS2 and MS3, if the results of the complete sample are compared with those of low- and high-rise buildings, it can be observed that the parameters of the complete sample are more adequate to describe the behaviour in high-rise buildings.

6. Conclusions

In this study, the influence of the buildings' height on the degradation of natural stone claddings was assessed through a condition-based maintenance model. The literature review shows that claddings at the top of buildings are more prone to degradation. These elements are more exposed to wind loads, temperature variations, and wind-driven rain action. On the other hand, claddings at the bottom of the buildings are more subjected to pollutant concentrations. From a statistical analysis of the anomalies observed in the NSC database, these results are confirmed. The anomalies presented in high-rise buildings are mainly caused by wet–dry cycles and the action of water, while in low buildings, they are caused by chemical and biological actions. Based on that, and in order to understand whether the degradation curves of tall and short buildings are statistically different, the degradation process in these buildings was analysed. The results confirm that NSCs are more durable in low buildings than in high-rise buildings. The higher exposure to environmental loads of the tall buildings increases their degradation process. Later, the impact of these differences on the maintenance requirements was assessed. For that purpose, three maintenance strategies were analysed. This revealed a strong influence on service life. Although high-rise buildings present a lower service life when maintenance is not carried out, when associated with maintenance activities, their service lives are longer than those obtained for low buildings. This demonstrates that the degradation pattern of high- and low-rise buildings is different, and the use of the complete sample can introduce considerable uncertainties in modelling the degradation pattern of stone claddings. The use of the adequate degradation curve is essential for the correct modelling of the claddings' behaviour. Furthermore, no assumptions should be made regarding the behaviour of claddings based only on their degradation curve, especially when considering maintenance activities.

Since the different types of stone have different degradation patterns, strengths, and vulnerabilities, to increase the reliability of the results, degradation curves for the different types of stone should be used. However, this analysis is outside the scope of the present study, and as the sample is being complemented, more detailed analyses, such as this one, will be carried out.

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