Proactive maintenance of natural stone claddings in current buildings

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Extended abstract

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1. Introduction

This study intends to propose a plan of maintenance for natural stone claddings. For that, the impact of the maintenance actions on the durability of these claddings should be considered. In the past, the maintenance of buildings and components was often neglected. Nevertheless, in the last decades, the maintenance has gaining importance in the construction sector. The sector recognises that the lack of maintenance promotes the occurrence of anomalies, which leads to a significant increase of the degradation of the housing stock. If this degradation reaches the maximum acceptable degradation level, the users' safety is jeopardised and, therefore, the building may reach the end of its service life [1]. To reinvert this situation, the adoption of maintenance is advisable or even mandatory, to ensure that the buildings or components can fulfil minimum performance requirements.

To avoid achieving an extreme degradation state, adequate maintenance plans should be defined, in order to identify when the maintenance activities must be carried out [2] and help the buildings' managers to understand which specific type of maintenance should occur, whether it is a more smoothing action or more profound, to avoid additional costs.

An adequate maintenance plan must define when and how to intervene, that is, determine which are the actions of maintenance that must be carried out in the element under study, but also which are the periodicities for those actions, helping to control the anomalies that might occur over the buildings' life cycle. These plans are crucial to optimize the costs and resources applied for the maintenance of buildings and components [3].

2. Preventive maintenance plan

This study intends to elaborate a preventive maintenance plan for natural stone claddings (NSC) directly adhered to the substrate. The maintenance aims at executing a set of actions to help maintain the element with acceptable characteristics throughout its service life [4]. This maintenance plan is part of the maintenance management of a building. A building manager should have a maintenance plan, which comprises the description of the actions to be performed, when and how they should be performed [2], in order to avoid the premature total replacement of an element, and to adopt prompt maintenance in order to mitigate the degradation processes of the building components.

The elements of a building that require maintenance actions are designated by maintenance source elements (MSE). A building is composed by many different MSE, and each one has its own characteristics in terms of degradation conditions. These MSE can be divided into three levels, ranging from level 1, which corresponds to general elements (built elements, finishes, instalations, and others) to level 3, which corresponds to more specific components (foundations, exterior walls, accessible roof, among many others) [4]. Level 3 can still be more detailed and divided into four levels [2], for example, for NSC: **Level 1**: vertical exterior façade; **Level 2**: cladding; **Level 3**: discontinuous; **Level 4**: stone plates.

For the definition of a maintenance plan, the service life of the element should be estimated, to know which are the more frequent anomalies and about those, determine the actions of maintenance that must be carried out. The costs associated with these actions and periodicities should also be determined, for each maintenance action considered. In this study, the main actions performed in natural stone claddings are: i) inspections, which are essentially visual but can also be aided by non-destructive tools *in situ* [8]; this action helps to understand when the maintenance actions should be carried out on the element, in order to mitigate the anomalies observed in the cladding under analysis [3]; ii) cleaning operations, which are simple actions of maintenance, in order to remove dirtiness, stains or biological agents, and other visual anomalies; and iii) the repair or replacement (total or partial), which aids to correct certain anomalies.

The definition of a preventive maintenance plan is the main goal of this work. For that, the different actions that should be carry out are identified, as well as their frequencies. These different actions are essential so that the element continues to fulfil the minimum performance requirements and to help to postpone the end of service life, without excessive costs. The actions mentioned, to be effective on the element, must be done in a certain time, which are determined from the literature. The life cycle costs (LCC - Life Cycle Costing) associated to this maintenance plan were determined, in order to evaluate the costs during the claddings' life cycle of during the time horizon adopted for the definition of the maintenance plan.

2.1 Maintenance actions and their periodicity

In this study, the preventive maintenance plan established to natural stone claddings, encompass the following actions:

i) inspections, which is mostly visual, but can be aided using non-destructive diagnostic techniques [11];
ii) cleaning actions, including brush, water jet, application of diluted bleach and a fungicide product [8] (in the presence of graffiti, the cleaning is based on stripper and water jet). After a cleaning operation, a hydrophobic impregnator waterproofing sealer can also be used, as a protective layer in the façade;
iii) repair and local replacement, which correspond to more profound actions;
iv) total replacement, that are made when the cladding reaches the end of their service life, i.e. when the cladding no longer meets the minimum performance requirements [8].

The frequencies of each one of the actions considered were defined based on the literature and from bibliographic references (Table 1). The costs associated to each one of these actions were determined from the price generator CYPE. After gathering all the necessary information, a sensitivity analysis is performed.

3. Sensitivity analysis

This sensitivity analysis focuses on two scenarios, scenario A, which analyses the time horizon of the maintenance plan and, scenario B, which analyses the sensitivity of life cycle costs, for different rates. In Scenario A, three hypotheses were tested for the time horizon: **Scenario A.1**: 30 years; **Scenario A.2:** 70 years; **Scenario A.3**: 150 years. For Scenario B, four hypotheses were analysed for the rates applied in the estimation of life cycle costs: **Scenario B.1**: Costs with inflation rate [PORDATA, 2020] and without risk rate; **Scenario B.2**: Costs with inflation rate [PORDATA, 2020] and with risk rate [PORDATA, 2020]; **Scenario B.3**: Costs without inflation rate and with risk rate [PORDATA, 2020]; **Scenario B.4**: Costs without inflation rate and without risk rate.

Table 1 - Summary of the periodicity of the actions considered in the maintenance plan

		Periodicities of the actions				
Code	Actions	Yearly	Two-year	Five-year	Decennial	Other (years)
A1	Inspection		x	x		
A2	Cleaning				x	
A3	Protection-waterproof treatment				x	
A4	Light intervention					20
A4.1	Water jet and biocide					20
A4.2	Repair of joints					20
A4.3	Stone replacement					20
A4.4	Crack repair: medium opening					20
A4.5	Crack repair: large opening					20
A4.6	Consolidating					20
A5	Total replacement					70

Table 2 shows the results obtained for scenario B. The sensitivity analysis allows choosing the time horizon or period of analysis in scenario A and the choice of the discount rate in scenario B. In this study, a time horizon of 150 years was selected (to ensure that the stone claddings are replaced at least one time over the period under analysis) and the discount rate presented in scenario B.3 was selected (around 6%).

Table 2 - Summary table of the rates adopted for Scenario B

	Year 2020			
SCENARIO B	**B.1**	**B.2**	**B.3**	**B.4**
Inflation rate	0.30%	0.30%	0.00%	0.00%
10-year treasury bond rate	0.80%	0.80%	0.80%	0.80%
Risk rate	0.00%	5.00%	5.00%	0.00%
Discount rate	1.10%	6.10%	5.80%	0.80%

4. Preventive maintenance versus condition-based maintenance

The preventive maintenance plan defined based on the literature was compared with a condition-based maintenance plan. Both plans present the same costs for the maintenance action considered, the same time period, and the same discount rate (6%). The two plans differ in the number of actions and their periodicity, since in the case of the condition-based plan, an inspection is carried out that will determine whether an action will be performed. These plans are modelled based on a on-going research project at the Instituto Superior Técnico [11], which is based on real data, in which the severity of degradation (S_w), the efficiency index (EI) and costs are compared. The severity of degradation is obtained by Equation (1).

$$Sw = \frac{\sum(A_n * k_n * k_{a,n}) + \sum(A_j * k_n * k_{a,n}) + \sum(A_f * k_n * k_{a,n}) + \sum(A_i * k_n * k_{a,n})}{A * \sum(k_{max})} \quad (1)$$

In this equation A_n define the área of the cladding affected by surface anomalies, the A_j the area of the cladding with anomalies in joints, A_f the area of cladding with bond-to-substrate anomalies and A_i the area of cladding with the loss of integrity anomalies, these areas are quantified in square meters. The k_n é is a multiplicative factor of the anomaly *n* depending on the degradation condition and the $k_{a,n}$ represents a "weighting coefficient corresponding to the relative weight of each anomaly" [11].

The severity of degradation consists of five degradation conditions, where degradation A is the most favourable condition and degradation E is the most unfavourable condition, as described in Figure 1. Table 3 shows the percentage of the severity degradation for each of the degradation conditions.

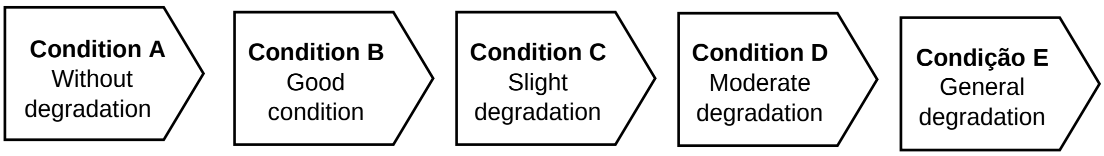

Figure 1 - Classification system for the degradation condition of natural stone coatings (adapted from [14, 15])

Table 3 - Severity of degradation range for each degradation condition (adapted from [14,15])

Degradation Condition	Severity of degradation, S_w
A	$S_w \leq 1\%$
B	$1\% < S_w \leq 8\%$
C	$8\% < S_w \leq 20\%$
D	$20\% < S_w \leq 45\%$
E	$45\% \geq S_w$

The efficiency index (EI) evaluates the efficiency of a maintenance strategy, i.e., this EI can evaluate the efficiency of a maintenance strategy to keep the natural stone cladding under more favorable conditions of degradation [10], for example, the lower the degradation of the natural stone cladding, the higher its efficiency index will be.

The costs of the actions used in this modelling are the costs previously determined, based on the price generator, CYPE (Table 4). Three maintenance strategies were analysed, to compare the two plans: **Maintenance Strategy 1**: Total Replacement; **Maintenance Strategy 2**: Total Replacement and minor intervention; **Maintenance Strategy 3**: Total Replacement, minor intervention, and cleaning operations.

Table 4 - Costs used for each intervention (€/m^2)

Interventions	**Costs (€/m^2)**
Total replacement (TR)	139.58
Minor intervention (MI)	59.25
Cleaning operation (CO)	45.01

4.1 Results and discussion

In the preventive maintenance plan, a service life of 70 years was considered for the natural stone claddings [6]. In this chapiter the modelling is done with a Weibull distribution. Therefore, for the preventive plan, the modelling for the different scenarios considers that the cladding must be subjected to a total replacement after 70 years, while the service life for the condition-based maintenance plan increases depending on the interventions performed. In each maintenance strategy (**MS**) ca exist total replacement (**TR**), minor intervention (**MI**) and cleaning operation (**CO**).

In the maintenance strategy 1- MS1- (only total replacement), the two maintenance plans present close efficiency index values, although the IE is higher for the condition-based maintenance plan and has a slightly lower number of interventions. For the condition-based maintenance plan, the severity of degradation presents more constant values, as opposed to the preventive maintenance plan, which present more variable results and being in the condition of degradation C at the time when it was defined that the total replacement of the cladding must be carried out (year 70). This result reveals that the cladding is replaced before reaching the end of its service life, which is conventionally defined as corresponding to a severity of degradation of 20%. This reveals that the non-existence of inspections anticipates the cladding's total replacement, which has economic and environmental impacts.

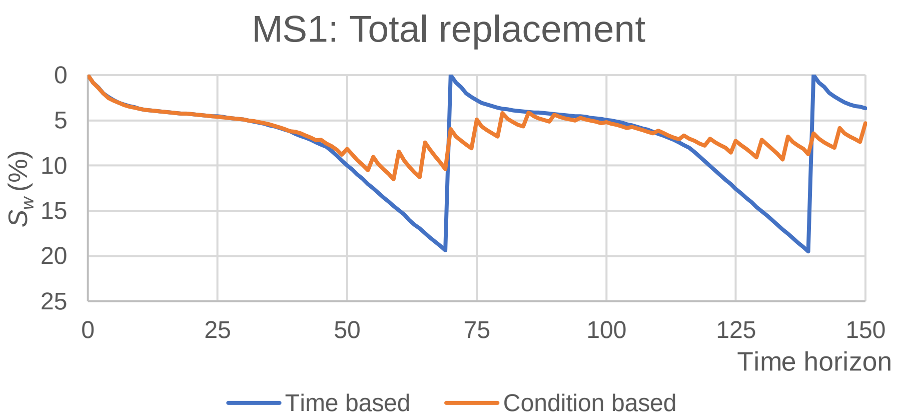

Figure 1 - Maintenance Strategy 1: Comparison of the S_w index

Figure 3 presents the comparison of the maintenance costs for the two maintenance plans. A significant difference at the level of the final cost can be observed since the cost of the preventive maintenance plan is more than a half of the cost of the condition-based plan. This situation is due to the number of inspections that were carried out in the condition-based maintenance plan. The results reveal that, in terms of costs, the preventive plan is more advantageous.

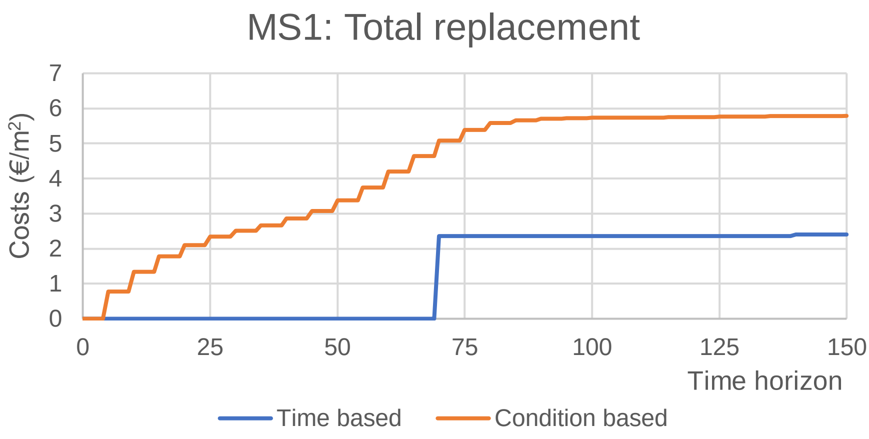

Figure 3 - Maintenance Strategy 1: Comparison of the maintenance costs (€/m^2)

In the maintenance strategy 2- MS2- which includes the total replacement and minor interventions (Figure 4), the severity of degradation, for both plans, are always below 8%, which shows that these plans maintain the natural stone claddings always between conditions A and B (most favourable). Figure 5 shows the comparison between the costs of the two maintenance plans. Both strategies present similar efficiency indexes. The preventive maintenance plan although showing a slightly higher EI, also presents almost the triple of the number of interventions, when compared with the condition-based maintenance plan, which implies that the preventive plan presents an overly high cost.

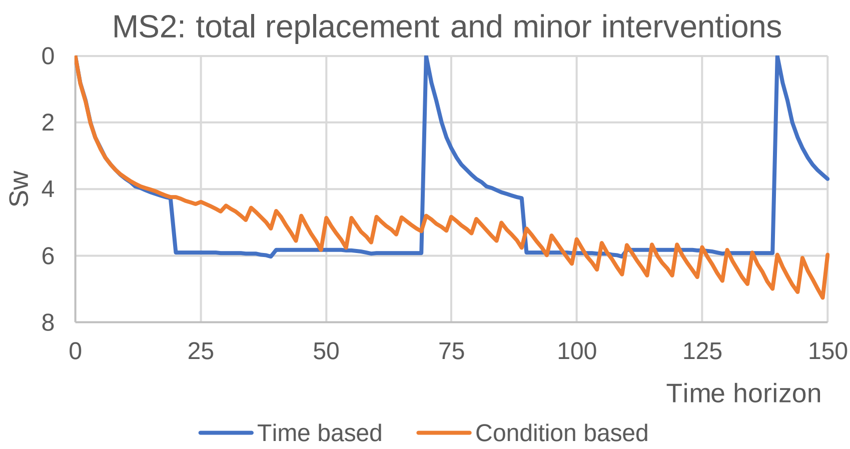

Figure 4 - Maintenance Strategy 2: Comparison of the S_w index

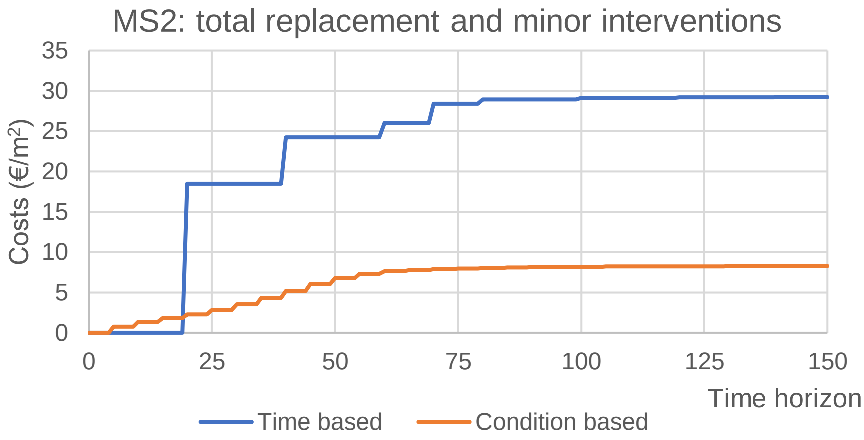

Figure 5 - Maintenance Strategy 2: Comparison of the maintenance costs (€/m^2)

For the maintenance strategy 3- MS3- in which total replacement, minor interventions and cleaning operations are adopted (Figure 6), both maintenance plans maintain the claddings in severity of degradation indexes below 7% (i.e., between conditions A and B).

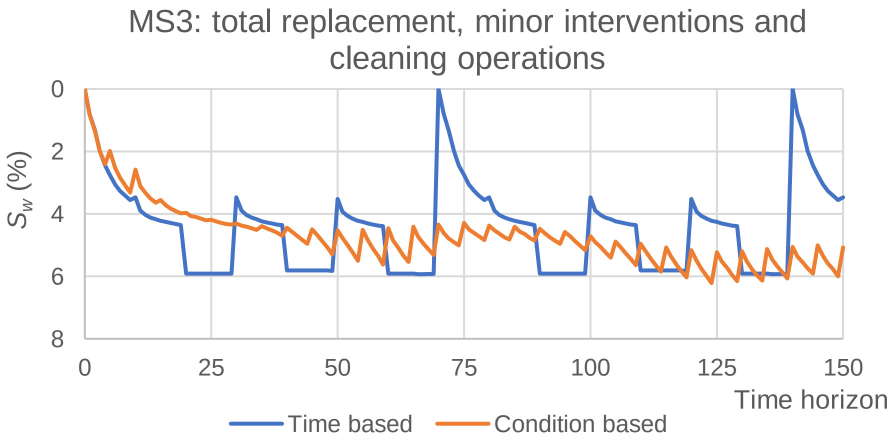

Figure 2 - Maintenance Strategy 3: Comparison of the S_w index

In this strategy, both plans present almost identical EI. Once again, the number of interventions for the preventive maintenance plan is twice the number adopted in the condition-based plan, but the final cost does not show a higher discrepancy between the two plans, although the preventive maintenance plan remains slightly higher (Figure 7). The choice of the most favourable plan, in this situation, depends on the building managers, who must decide whether they prefer to have a plan with actions previously scheduled (which allows a more efficient management of funds) or whether they prefer to carry out inspections and decide based on the degradation condition of the claddings.

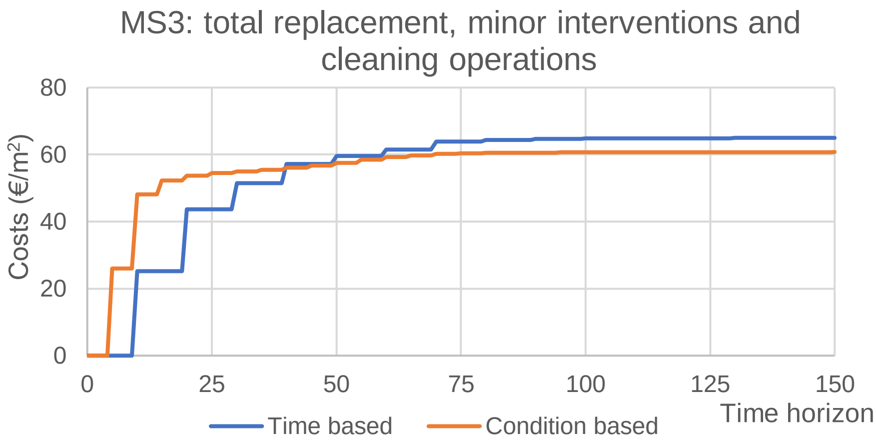

Figure 7 - Maintenance Strategy 3: Comparison of the maintenance costs (€/m²)

Table 5 presents the differences in the number of interventions for the preventive and for the condition-based maintenance plans. The preventive maintenance plan presents a higher number of interventions, and, consequently, higher maintenance costs.

Table 5 - Number of interventions for each maintenance plan and strategy

	Number of interventions					
	Condition-based			Preventive		
	TR	MI	CO	TR	MI	CO
MS1	1.7	-	-	2	-	-
MS2	0.5	2.1	-	2	6	-
MS3	0.3	2	5.6	2	6	7

Table 6 shows the differences in the efficiency index (EI) and costs for the different strategies. Although the EIs are remarkably close for MS2 and MS3, the preventive maintenance plan prevails, while the costs of MS2 for the preventive maintenance plan are extremely high due to the exaggerated number of interventions.

Table 6 - Efficiency index and costs (€/m²) for each maintenance plan and strategy

	Efficiency index	
	Condition based	Preventive
MS1	0.936	0.927
MS2	0.947	0.951
MS3	0.953	0.955

	Costs	
	Condition based (€/m²)	Preventive (€/m²)
MS1	5.79	2.40
MS2	8.27	29.22
MS3	60.78	64.98

4.2 Optimization of the preventive maintenance plan based on historical data

According to the analysis of these strategies, the Maintenance Strategy 2 was selected, since presents a compromise solution between efficiency and cost. Moreover, the minor interventions already assume the adoption of cleaning operations, which implies that in MS2, the two actions are carried out simultaneously, optimizing the cost of using scaffolding (which presents a significant impact on the maintenance costs). This strategy is modelled ensuring a close relationship with historical data and information about the degradation processes of 203 stone claddings used to propose the condition-based maintenance plan, adopted for comparison and validation in this study [7]. In this sense, the condition-based plan reveals that the adoption of

MS2 leads to an estimated service life of 148 years. Based on this information (which relies on historical data), a service life of 140 years is adopted for the preventive maintenance plan, considering that the adoption of minor interventions increases the service life of the natural stone claddings. In the optimised preventive maintenance plan, the number of interventions is reduced, since the previous results show that unnecessary actions were carried out that have considerably increased the maintenance costs without improving the EI proportionally.

Table 7 - Optimized maintenance strategy 2: life cycle and number of interventions

Maintenance strategy 2 - MS2					
Life cycle		**Number of interventions**			
Condition based (years)	**Preventive (years)**	**Condition based**		**Preventive**	
		TR	**LI**	**TR**	**LI**
148	140	0.5	2.1	1	3

Therefore, the frequency for interventions was changed from 20 to 35 years. With these small changes the number of interventions decreased from 8 to 4 interventions. Both costs and EI are similar, when comparing the condition-based and the optimised preventive maintenance plan.

Table 8 - Optimized maintenance strategy 2: Comparison of costs (€/m^2) and efficiency indexes for the two maintenance plans

Maintenance strategy - EM2			
Costs		**Efficiency index**	
Condition based (years)	**Preventive (years)**	**Condition based**	**Preventive**
8.27	8.88	0.947	0.944

This new modelling is an optimization of the preventive maintenance plan, where the service life is maximized, without excessive and unnecessary intervention numbers, and the most interesting point is that in this plan there is no need to have periodic inspections every 5 years, as in the case of the maintenance plan based on the condition, because the preventive maintenance plan is already stipulated from the beginning (which allows a more planned management of funds over time).

5. Conclusions

Over the last few years, the maintenance has gained great relevance, especially in new buildings, as this practice has proved to be crucial for the optimisation of costs and resources. The definition of a maintenance plan during the design stage allows a rational management of funds, avoiding unnecessary costs while extending the service life of materials, thus guaranteeing that the buildings fulfil minimum performance requirements during their service life.

This study can be useful for building managers, giving some information regarding the different maintenance strategies that can be adopted and the impact of maintenance planning on the durability, service life, performance and efficiency and life cycle costs of buildings and components. Based on this study, the stakeholders can choose a given strategy and plan, selecting if they prefer a plan based on the buildings' condition, which does not present any maintenance fixed periodicities, and is based on inspections, or the preventive maintenance plan, a plan that preschedule the maintenance actions and periodicities, allowing knowing in advance when the maintenance costs will be spent.

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