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Opportunity-Based Maintenance of Buildings' Envelope

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Abstract. *More than half of the building's life-cycle costs correspond to maintenance costs. Nevertheless, maintenance actions are, generally, conditioned by subjective criteria and carried out at inopportune times, which implies that one third of the maintenance costs are improperly incurred. Buildings are multi-component systems and, therefore, the adoption of opportunistic maintenance policies allows reducing the maintenance costs and the number of interventions, while maximizing the service life and the efficiency of the resources available. In this study, an opportunistic maintenance plan is proposed for the buildings' envelope, combining the maintenance needs of four elements: rendered facades; ceramic claddings; window frames; and pitched roofs ceramic claddings. For this purpose, a condition-based maintenance model is used. The maintenance model is based on stochastic degradation models for the individual components of the system. The optimization of these policies will identify the best maintenance schedule and combination of maintenance activities, finding the optimal trade-off between disruption of the buildings' use, maintenance costs and their service life. The application of these opportunistic maintenance policies in the building envelope elements allows mitigating the degradation of these elements over the buildings' life cycle and, consequently, increasing the economy, quality, and aesthetic perception of our cities. This methodology will change the way that maintenance plans are defined, and interventions are prioritized.*

Keywords: *Opportunistic maintenance; Condition-based maintenance; Service life; Life-cycle costs; Buildings' envelope*

1 Introduction

Stakeholders start to recognize that buildings are too valuable to be neglected (Wanigarathna et al. 2019), but the planning of their maintenance remains a critical issue. Maintenance costs can represent more than 50% of the building's life-cycle costs (Kim et al. 2019), and due to the uncertainties and inefficiencies involved in maintenance planning, about 33% of the maintenance costs are lost in unnecessary or inadequate maintenance actions (Mobley 2002, Dejaco et al. 2017). Therefore, the development of accurate tools to support the maintenance planning in a systematic and optimized way is needed (Ruparathna et al. 2018).

Compared to reactive maintenance, proactive maintenance shows the potential to enhance the infrastructures' performance (by preventing problems that can predictably occur during the component's lifetime), while the long-term costs and risks are reduced (CIBSE 2014). However, the benefits of the proactive maintenance policies can be further promoted when combined with opportunistic maintenance policies (Koochaki et al. 2012, Vu et al. 2020).

In conventional maintenance strategies, the dependence between the individual components of an infrastructure is ignored (Yang et al. 2019, Ferreira et al. 2020). However, buildings are multi-component systems, and the performance of one component will directly affect the performance and the maintenance scheduling of the other components. With opportunistic maintenance policies, maintenance activities of two or more components can be grouped, taking advantage of the scale economies of one ongoing activity (Vu et al. 2020), to increase their overall efficiency. A significant part of the maintenance costs is related with scaffolding or other means of access (Ferreira et al. 2021) and specialized tasks, personnel, and equipment. In this sense, the positive economic dependence between the components implies that the cost of joint maintenance of a group of components is less than the total cost of individual maintenance of these components (Hu et al. 2020). In opportunistic maintenance, a “convenient” maintenance of components is adopted, by taking advantage of scheduled or unscheduled interventions (Lind and Muyingo 2012). The key aspect of this policy is to be able to define when a component should be maintained, during its service life, to gain cost effectiveness advantages. Therefore, by changing the perspective, new options are added to the decision-making systems, enhancing the performance and functionality of the infrastructure (Zhang and Wang, 2017).

Therefore, this study proposes to explore the concept of opportunistic maintenance policies to optimize the maintenance planning in multi-component systems, using a condition-based maintenance model. The maintenance model is based on stochastic degradation models for the individual components of the system. The optimization of these policies will identify the best maintenance schedule and combination of maintenance activities, finding the optimal trade-off between disruption of the buildings’ use and maintenance costs. In this sense, an opportunistic maintenance plan is proposed for the buildings’ envelope, combining the maintenance needs of four elements: rendered facades; ceramic claddings; window frames; and pitched roofs ceramic claddings. The application of these opportunistic maintenance policies in the building envelope elements allows mitigating the degradation of these elements over the buildings’ life cycle and, consequently, increasing the economy, quality, and aesthetic perception of our cities. This methodology will change the way that maintenance plans are defined, and interventions are prioritized.

2 Condition-Based and Opportunity-Based Maintenance

A methodology based on the Petri nets formalism is used to model the degradation and maintenance of the individual’s elements of the building’s envelope. The evolution of the degradation condition of the elements over time is modelled in a stochastic way. Maximation likelihood indicators and genetic algorithms are used to fit the degradation curve to the historical data, which is based on the fieldwork inspection of a sample composed of 100 rendered façades, 195 ceramic claddings, 112 aluminium window frames and 146 pitched roofs’ ceramic claddings.

In this study, the maintenance model based on Petri nets is used to define a condition-based and an opportunistic maintenance policy. The condition-based maintenance policy is based on the regular monitoring of the component’s condition (by visual inspections). In the opportunistic maintenance policy, an opportunistic maintenance zone is defined, representing the window of opportunity to perform a given maintenance action, i.e. the time from which the action is necessary until it leads to an unacceptable condition. This opportunistic maintenance zone will depend on the degradation model of each element.

The degradation condition of each component is determined by a numerical index, called severity of degradation, S_w (Equation 1). This numerical index is translated into five discrete degradation conditions, ranging from A (no visible degradation) to E (generalised degradation), portraying the overall condition of the envelope components (Ferreira et al. 2023).

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

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 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); and Σk_{max} the sum of the multiplying factors of the highest degradation condition of each anomaly type. Since the severity of degradation corresponds to the ratio between the area affected by the anomalies observed, weighted according to their severity, and a reference area equivalent to the total cladding area with the highest possible degradation condition, the index ranges between 0 and 100%.

In single-component systems, proactive maintenance policies are often successfully implemented through the definition of a performance threshold; upon reaching this threshold, a maintenance activity is initiated. However, this approach may not result in an optimal solution for multi-component systems, because there are several dependencies between the components. Therefore, to overcome this limitation, a cost-effective opportunity-based maintenance model is proposed in this study to achieve an optimal maintenance scheduling of the buildings' envelope components, considering the economic dependence between the components.

In this study, four maintenance actions are considered: i) inspections, to characterise the degradation condition of the building components, without any impact on its condition; ii) cleaning operations, to remove superficial and aesthetic anomalies that occur in the building components, and the possible correction of the causes that are at their origin; iii) minor interventions, including cleaning actions and partial repair or replacement of elements; iv) total replacement at the end of service life, corresponding to the replacement of the building component. The impact of each maintenance activity in the individual's elements of the buildings' envelope is modelled by estimating the reduction on the severity of degradation index through the adoption of a given maintenance action (Table 1). In this sense, it is assumed that the impact of the maintenance activities will be imperfect (e.g. the removal of stains by cleaning does not set the façade as "good as new", if the façade presents cracking that are not corrected with that specific maintenance action).

Two maintenance strategies (MS) are analysed: MS1 - a combination of total replacement and minor interventions, in order to delay the end of service life of building components, thus reducing the number of total replacements over the building's lifetime, without compromising the safety and relevant parameters related to the building's performance; and MS2 - total replacement, minor intervention, and cleaning operations, to assess the impact of a simple and more economical action in the lifetime performance of buildings' envelope components.

The analysis of different maintenance planning is carried out, in which the impact of different opportunistic maintenance zones on the schedule, performance and costs is assessed. For the definition of the opportunistic maintenance policies, another important parameter that is assessed is the time interval between inspections, since the condition-based maintenance is based on regular monitoring. The optimal time interval between inspections of the individual components is different from each other. Therefore, to find the optimal time interval between inspections for the multi-component system, a methodology based on the metric value of information is applied. This methodology allows assessing the impact of additional information (in this case, more information about the inspections carried out) on the decision-making process that needs to ascertain. Therefore, for each building envelope components (renderings, ceramic cladding, aluminium window frames and pitched roofs' ceramic claddings), the condition-based maintenance model based on Petri nets is executed. For each component, the average instant of application of the different maintenance actions and their average cost is estimated (based on the histograms of the probability of each action being required at that time) - Equations (2) and (3). In this study, a time horizon of 50 years is considered, since it is the conventional value adopted for the service life of current buildings.

Table 1. Costs and impacts of the different maintenance activities performed in the buildings' envelope components.

Building component	Maintenance action	Cost [€/m^2]	Application zone	Impact of the maintenance activity [%]		
				P_A	P_B	P_C
Rendered facades	Inspection	1.03	All	-	-	-
	Cleaning operation	26.88	B	61.1	38.9	
	Minor intervention	34.68	C	61.3	38.7	
	Total replacement	36.68	D, E	100.0	-	-
Ceramic claddings	Inspection	1.03	All	-	-	-
	Cleaning operation	27.48	B	30.6	69.4	-
	Minor intervention	65.77	C	3.1	58.5	38.5
	Total replacement	68.85	D, E	100.0	-	-
Aluminium window frames	Inspection	1.03	All	-	-	-
	Cleaning operation	14.06	B	16.9	83.1	-
	Minor intervention	31.17	C	0.0	30.4	69.5
	Total replacement	125.35	D, E	100.0	-	-
Pitched roofs ceramic claddings	Inspection	1.03	All	-	-	-
	Cleaning operation	14.00	B	61.5	38.5	
	Minor intervention	24.14	C	70.8	24	5.2
	Total replacement	59.12	D, E	100.0	-	-

$$Instant_{average} = \sum_{i=1}^{200} i * p_{intervention} \tag{2}$$

$$Cost_{average} = \sum_{i=1}^{200} \frac{cost_{intervention}}{(1+0.06)^i} * p_{intervention} \tag{3}$$

3 Results and Discussion

Figures 1 and 2 show the condition-based and the opportunity-based maintenance plans, respectively, for the four building envelope elements analysed in this study. The data used for the maintenance schedule are obtained from the simulation model, i.e. from the first simulation run of each building component. The planning is defined based on the average values of the intervention instants, adjusted in order to maximize the number of interventions at the same time, thus reducing indirect costs with a high weight in the overall maintenance costs (e.g. scaffolding).

Both plans correspond to life-cycle maintenance models, integrating the stochastic modelling of the degradation process, as well as the inspection and maintenance/repair processes performed on the buildings' envelope components. The condition-based maintenance model is by itself already an optimised model, which has been published by the authors (Ferreira et al. 2023). This model has numerous advantages when compared to reactive maintenance or even preventive maintenance, maximizing the durability of the elements, without compromising their performance while reducing maintenance costs. Previous studies by the authors (Ferreira et al. 2021, 2023) reveal that maintenance activities can improve the components' service life between 20% and 200%, thereby reducing the number of replacements by between 25% and 80% (depending on the materials and exposure conditions). Moreover, condition-based maintenance allows a reduction in life cycle costs of around 70%, when compared with reactive maintenance strategies.

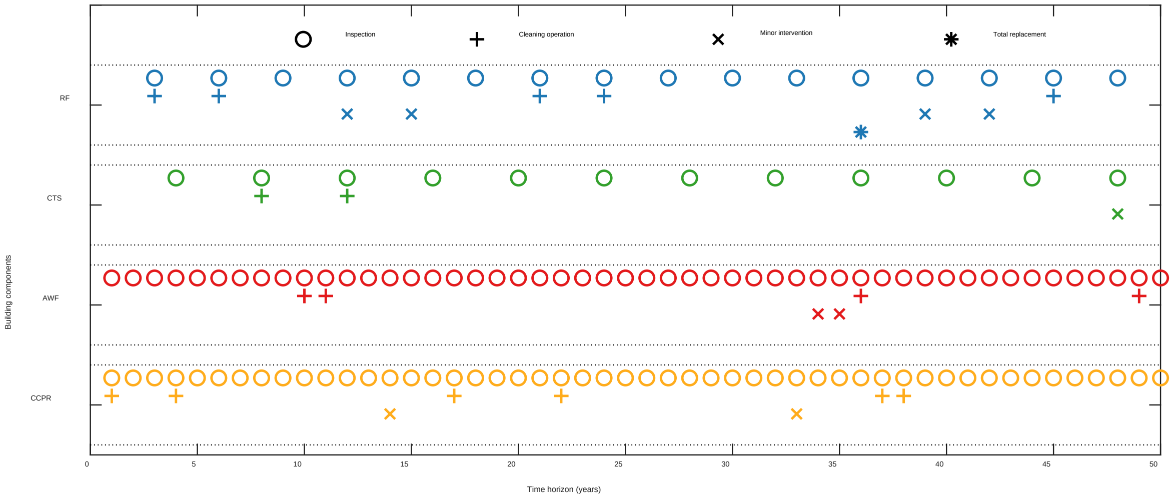

Figure 1. Condition-based maintenance plan for the building envelope elements.

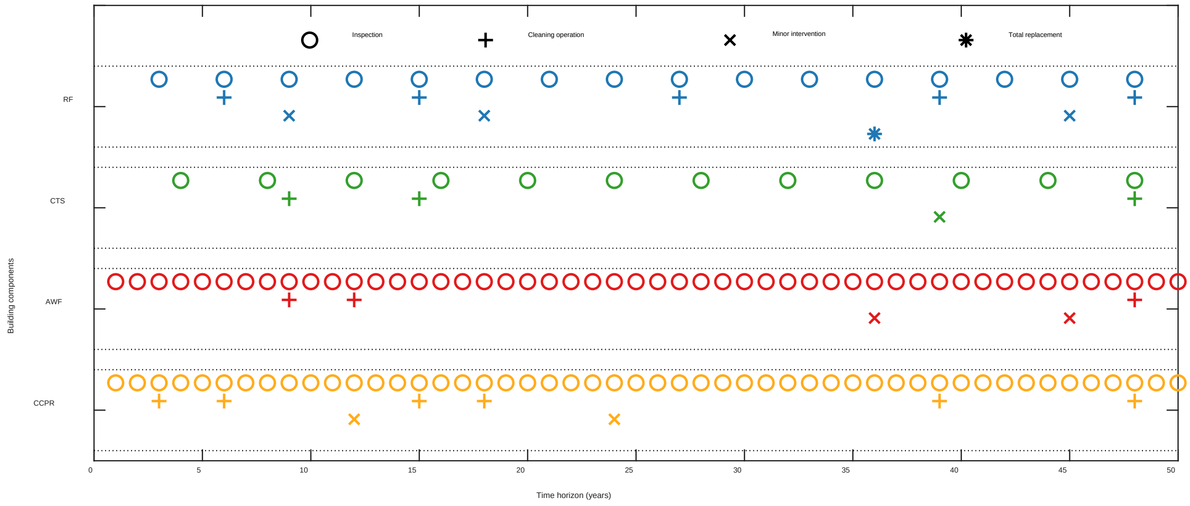

Figure 2. Opportunity-based maintenance plan for the building envelope elements.

Nevertheless, this study intends to discuss the advantages of adopting an opportunistic maintenance strategy, to optimize the maintenance planning in multi-component systems, finding the optimal trade-off between durability and costs. Tables 2 and 3 presents the results obtained.

Table 2. Comparison between the two maintenance plans for maintenance strategy 1 (MS1).

Component	Condition-based (€/m²)	Opportunity-based (€/m²)	Difference between the two maintenance plans (€/m²)	Reduction of maintenance cost with opportunity-based maintenance (%)
Façade	72.77	61.87	10.90	14.97
Window frames	14.19	8.64	5.55	39.12
Pitched roofs	26.84	24.36	2.48	9.24
Total	113.80	94.87	18.93	16.63

Table 3. Comparison between the two maintenance plans for maintenance strategy 2 (MS2).

Component	Condition-based (€/m²)	Opportunity-based (€/m²)	Difference between the two maintenance plans (€/m²)	Reduction of maintenance cost with opportunity-based maintenance (%)
Façade	134.05	104.07	29.98	22.37
Window frames	29.02	22.26	6.76	23.30
Pitched roofs	56.28	52.63	3.65	6.49
Total	219.35	178.95	40.40	18.42

Fixed costs, namely scaffolding installation, strongly influence the life-cycle costs and, for building envelope elements and, therefore, the results reveal that the adoption of opportunistic maintenance plans encompasses a reduction of maintenance costs of 18.93 €/m^2 for MS1 and of 40.40 €/m^2 for MS2. These values become more significant the higher the housing stock managed. For example, in the sample analysed, these values correspond to a saving of 160,569.34 € for pitched roofs' ceramic claddings (146 pitched roofs' ceramic claddings located in Portugal, with a total area of 43,991.6 m^2) for MS2, and a saving of 126,218.40 € for the ceramic claddings analysed (195 ceramic claddings located in Portugal, with a total area of 11,579.7 m^2).

4 Conclusions

This study discusses the advantages of adopting opportunity-based maintenance plans. Condition-based and opportunity-based maintenance plans are proposed, identifying the opportunistic maintenance zones on the schedule, considering the optimal trade-off between maintenance costs and the buildings' use and service life. The opportunity-based maintenance approach proposed in this study allows defining an optimal planning of the maintenance activities in building envelope elements according to building features and stakeholder' requirements. Furthermore, the consequences of postponing or anticipating maintenance activities can also be considered, as well as the impact of emergency maintenance. A long-term maintenance plan is subjected to uncertainty and unforeseen events, and, therefore, the proposed model can redesign the maintenance plan, in order to assess the consequence of these changes over time and help in the decision-making process. This optimization problem is solved using genetic algorithms and evolutionary strategies.

The results obtained reveal that opportunity-based maintenance allows a reduction of the global maintenance management costs, which has a relevant impact on the economic practicability of maintenance activities on built heritage. This approach enhances the durability, safety, and sustainability of the built heritage. The adoption of more efficient maintenance plans promotes the: i) reduction of the life-cycle costs, ii) increase of the resource efficiency during the buildings' repair or renewal, iii) increase of the asset value, iv) reduction of the social impacts of buildings' depreciation, and v) minimization of the consumption of raw materials. This methodology is extremely valuable for organisations that manage large sets of buildings, to prioritize maintenance activities and investments.

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