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Stochastic Petri net-based modelling of the durability of renderings

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ABSTRACT

In this study, a methodology to model and predict the life-cycle performance of building façades based on Stochastic Petri Nets is proposed. The proposed model evaluates the performance of rendered façades over time, evaluating the uncertainty of the future performance of these coatings. The performance of rendered façades is evaluated based on a discrete qualitative scale composed of five condition levels, established according to the physical and visual degradation of these elements. In this study, the deterioration is modelled considering that the transition times between these condition states can be modelled as a random variable with different distributions. For that purpose, a Stochastic Petri Nets model is used, as a formal framework to describe this problem. The model's validation is based on probabilistic indicators of performance, computed using Monte-Carlo simulation and the probability distribution parameters leading to better fit are defined as those maximizing the likelihood, computed using Genetic Algorithm. In this study, a sample of 99 rendered façades, located in Portugal, is analysed, and the degradation condition of each case study is evaluated through in-situ visual inspections. The model proposed allows evaluating: i) the transition rate between degradation conditions; ii) the probability of belonging to a given degradation condition over time; and iii) the mean time of permanence in each degradation condition. The use of Petri Nets shows to be more accurate than a more traditional approach based on Markov Chains, but also allows developing future research to consider different environmental conditions, maintenance actions or inspections, amongst other aspects of life-cycle analysis of existing assets.

1. Introduction

According to Jensen and Rozenberg [66], the net theory can be seen as "a system theory that aims at understanding systems whose structure and behaviour are determined by a combinatorial nature of their states and changes". The first proposal of nets of places and transitions, proposed by C. A. Petri [1], allows developing a non-idealizing methodology to concurrency and information flow, in organizational systems [2]. Petri nets are considered a mathematical and graphical tool for the formal description of systems whose dynamics are characterized as being concurrent, asynchronous, distributed, parallel, non-deterministic, and/or stochastic, mutual exclusive, and conflicting, which are typical features of distributed environments [3]. Therefore, Petri nets allow capturing the static and the dynamic nature of a real system, thus characterizing the rate of transition between states or conditions [4].

Due to their characteristics, Petri nets have been successfully applied in different fields of knowledge, namely in robotics [5], in the optimization of manufacturing systems [6,7], business process management [8], human computer interaction [9], amongst others. Petri nets are not widely used in the construction industry, and particularly in building asset modelling. Nevertheless, there are various works [10–14] that use Petri nets to manage resources, to estimate equipment availability and scheduling of tasks on the site-work during the building design process. On the other hand, recent work has been published on the use of Petri Nets to model the deterioration of other civil engineering infrastructures [15–21]. In the last decades, various authors proposed several extensions and adaptations of ordinary Petri nets; all of them based on the basic Petri net formalism, but presenting very different characteristics and assumptions, in order to adapt themselves to the phenomena under analysis. Consequently, there is a reasonable expertise in the application of Petri nets to different application domains, thus allowing transferring knowledge and methodologies from one field to another [22].

This study intends to evaluate the suitability and advantages of the use of Stochastic Petri Nets (SPN) as deterioration models in building

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Table 1
Description of the degradation conditions of rendered façades.

Condition level	Description
Condition A	Most favourable condition. Complete mortar surface with no visible degradation, with uniform colour, showing no dirt or detachment
Condition B	Mortar with a non-uniform surface with likelihood of localized voids determined by percussion, but no signs of detachment. Small cracking (0.25 mm to 1.0 mm) in localized areas and changes in the general colour of the surface might exist. Eventual presence of microorganisms.
Condition C	Mortar with localized detachments or perforations, revealing a hollow sound when tapped and detachments only in the socle, with easily visible cracking (1.0 mm to 2.0 mm) and showing dark patches of damp and dirt, often with microorganisms and algae.
Condition D	Mortar with an incomplete surface due to detachments and falling of mortar patches, showing wide or extensive cracking (≥ 2 mm) and very dark patches with probable presence of algae.
Condition E	Most serious condition, requiring an immediate corrective action, associated with incomplete mortar surface due to detachments and falling of mortar patches. Also revealing a wide or extensive cracking (≥ 2 mm), with very dark patches and probable presence of algae.

asset management. The main advantages of SPN are their graphical representation, allowing a better and more intuitive understanding of the modelling principles, and their versatility, allowing the modelling complex stochastic processes. In the particular case of deterioration modelling, and compared to the more traditional Markov Chains, SPN allow the seamless use of different probabilistic distributions. Furthermore, their versatility allow modelling, in a common framework, multiple aspects of asset management, including deterioration, maintenance, inspection, and decision-making. In this study, a model to predict the life-cycle performance of building façades based on stochastic Petri nets is proposed. To analyse the degradation condition of rendered façades over time, a set of Petri net models considering different probabilistic distributions are used to estimate the transitions times between condition levels. Since there are no closed form expressions for the probability distribution of the condition state at a certain time, Monte Carlo simulation is used to compute the likelihood of each model. However, the errors introduced by Monte Carlo simulation require the use of gradient-independent optimization methods, like Genetic Algorithms, to identify the optimal parameters of the probability distributions.

The sample analysed in this study comprises 99 renderings, located in Portugal, for which degradation condition was evaluated through in situ visual inspections. The classification system adopted in this study to evaluate the deterioration state of rendered façades is a discrete qualitative scale divided in five condition levels, proposed by Gaspar and de Brito [23,24], ranging between "no visible degradation" (condition A) and "generalized degradation" (condition E), which requires an immediate rehabilitation or maintenance action.

In the first part of this study, a traditional method, based on Markov chains is applied, in order to define a benchmark model. The benchmark model and the Petri net model with transition times exponentially distributed are used to validate the methodology proposed. The comparison of the models is possible since the stochastic Petri net with transitions exponentially distributed is equivalent to a finite Markov chain. After that, a set of probabilistic distributions are used to analyse the degradation condition of rendered façades over time. The information obtained from the Petri net models allows the identification of the degradation rate of rendered façades, characterizing the pattern that characterizes the loss of performance of these claddings over time. This information is crucial to identify the future need for interventions, optimizing the maintenance needs, and thus avoiding unnecessary cost associated with urgent interventions.

The outline of this paper is as follows: Section 2 provides a literature review concerning the classification system and modelling techniques used to model the evolution of the degradation in rendered façades; Section 3 introduces the concept of Petri nets, as well as the procedure used to predict the life-cycle performance of renderings. Finally, the discussion of the results is presented in Section 4 and conclusions are drawn in Section 5.

2. Literature review

The façades can be seen as the skin of the building, i.e. they can be considered the first layer of protection against the deterioration agents [25], thus being the element more prone to degradation. According to Flores-Colen and de Brito [26] the claddings' degradation level can influence the quality of the urban environment, since it affects the architectural appearance of buildings, which has a considerable effect on the physical comfort of inhabitants of larger cities [27]. Rendered façades are the most common type of cladding in Portugal [28]. In the present context of societies aiming at achieving a more sustainable use of resources, it is increasingly important to define rational maintenance strategies so as to avoid unnecessary costs [29–31]. For that purpose, it is essential to develop new and versatile tools to support the decision-making process regarding the instant in which maintenance actions must be performed, knowing the degree of uncertainty associated with the estimates [32]. To achieve this, the present work focuses on the use of probabilistic based methods for modelling performance, including Stochastic Petri Nets and Markov Chains.

The definition of maintenance strategies is, in general, related with the users' demands, i.e. more demanding users may demand a high level of performance, requiring that the cladding be replaced as soon as it starts to deteriorate; on the other hand, some users may accept a lower level of performance, thus minimizing the maintenance costs [67]. Consequently, the definition of maintenance strategies requires the condition assessment of rendered façades and the knowledge of their expected service life. According to Hertlein [33], condition-based maintenance by inspection planning can be a useful tool to reduce the life cycle costs, achieving a more rational and efficient way to manage maintenance budgets [34].

In the last decades, different studies [23,35–38] propose visual and physical scales to characterize the type, extension and severity of defects observed in rendered façades. Gaspar and de Brito [23] and Silva et al. [39] proposed a discrete scale to evaluate the degradation condition of rendered façades (Table 1).

This qualitative scale, based on the evaluation of the physical and visual degradation of rendered façades analysed during a comprehensive fieldwork, can be associated with a quantitative index that portrays the global performance of the façades. This numerical index, initially proposed by Gaspar and de Brito [23,24], expresses the global degradation of façade coatings through the ratio between the degraded area weighted as a function of its condition and a reference area, equivalent to the whole and having the maximum degradation level possible - Eq. (1).

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

where S_w is the degradation severity of the coating, expressed as a percentage; k_n is the multiplying factor of anomaly n, as a function of their degradation level, within the range $K = \{0, 1, 2, 3, 4\}$; $k_{a,n}$ is a weighting factor corresponding to the relative weight of the anomaly detected ($k_{a,n} \in \mathrm{R}+$); $k_{a,n} = 1$ by default; A_n is the area of coating