Stochastic models applied to the service life prediction of ETICS

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Extended abstract

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1. Introduction

When the concerns regarding the buildings' consumption of energy increase, the need for sustainable solutions in the construction industry arises. Since the thermal performance of buildings is an area with great opportunities for improvement, more and more efficient solutions emerge in the market [1]. ETICS (External Thermal Insulation Composite Systems) are one example of such solution. However, the performance of thermal insulation systems declines, because of the continuous effect of degradation agents.

In the present study, stochastic methods are applied to the analysis of the evolution of the degradation of façades with ETICS. The stochastic methods considered are logistic regression and continuous time Markov chains. The application of these two methods intends to: i) identify the probability of a façade to have a given degradation condition as a function of its age, its characteristics and the environmental conditions to which it is subjected; ii) determine in which time intervals there is a higher probability that the façade degradation transits from a condition level to the next one, by worsening its overall degradation; iii) identify the probability of ETICS reaching the end of their service life, during a given time frame.

2. Service life definition

To study the evolution of the degradation of buildings and their components, a clear definition of the related terminology associated to the concepts of service life and degradation is required. According to ISO 15686 [2], the service life of a component corresponds to the period during which the component performance meets or exceeds the established requirements. These requirements can relate to the safety of the building, its functionality, or the aesthetic appearance [3].

The buildings can be subjected to continuous interventions, with the objective of maintaining acceptable levels of performance, thus postponing the end of their service life [4]. Once the service life is reached, the building does not cease to perform its functions; it just diminishes its level of performance, to levels below the acceptable threshold.

3. ETICS systems

The comfort of the buildings can be improved when thermal insulation solutions are used [5]. ETICS are one solution that is applied to the external layer of the walls. However, there are alternative approaches to thermal insulation, namely the insulation on the interior side of the walls and the insulation in the air box of the wall, between the inner and outer layers of masonry.

External thermal insulation is the chosen solution, since it contributes to an improved energy efficiency of the buildings, by vastly reducing the effect of the thermal bridges, when compared to more traditional solutions [5, 6].

3.1 System components

ETICS are a multilayer system, in which the main component is the thermal insulation layer, which is applied in the form of boards fixed to the substrate. The thermal insulation layer is protected with outer layers that serve the purpose of mechanical reinforcement and preventing water from penetrating and jeopardizing the integrity of the system.

The substrate is the layer of the wall itself, upon which the whole system is applied. The boards of the thermal insulation component are made of either expanded polystyrene (EPS), extruded polystyrene (XPS), cork agglomerate, or mineral wool and they are fixed to the substrate using glue or mechanical fasteners. The most common material for the boards is EPS. The next layer is the base layer, which is made of mortar and has the function of embedding the reinforcement, attached to the boards, improving its mechanical behaviour, thus ensuring better durability of this solution. The outside layer is the final coating, serving an aesthetic purpose and providing watertight functionality to the inner layers.

3.2 Anomalies and probable causes

Since the moment that ETICS systems are applied, the continued action of the atmospheric agents takes its action on the materials' durability. To adequately model the evolution of the degradation, the effect of different anomalies must be considered, since the way they affect the façade is distinct.

To consider the differences between anomalies, classification systems were developed. In the context of the present work, the classification system developed by Amaro et al. [7] is considered, along the work of Silva et al. [8]. This system divides the anomalies into four different groups, according to their criticality in terms of conditioning the evolution of the degradation of the façades. The groups are: i) staining and colour or texture changes; ii) joint defects; iii) loss of continuity or integrity; iv) loss of adhesion.

Even though the anomalies are well documented, the factors that constitute their most probable causes are difficult to determine, because of the interaction between the various anomalies. Therefore, the most common factors are the presence of water, the exposure to atmospheric degradation agents and radiation, poor quality of the materials applied, inadequate design of the solution and poor conditions during the application of the system [9].

4. Field work

The field work has the objective of collecting adequate data to be used in the models considered for analysing the evolution of the degradation of the façades.

In the context of the present study, the field work comprised the preparation stage, the inspection stage, and the processing stage. These are further explained in the next section.

4.1 Methodology adopted for the investigation

The field work carried out in the present study allows obtaining valuable data to be used in the modelling of the evolution of the degradation of the façades.

The preparation stage of the field work comprised the statistical analysis of the existing sample of façades, to determine which characteristics need further treatment to increase the statistical representativeness. Buildings with ETICS systems were identified, so that inspections could be planned.

During the inspection stage, a campaign of inspections has been carried out, collecting visual evidence of the anomalies present in each façade, through visual inspections.

Finally, the data collected in field were treated during the processing stage, so that they could be used to define the models to be applied in the study of the evolution of the degradation of the material and the influence of the different characteristics of the façades and surrounding environment.

4.2 Sample analysed

The sample analysed comprises 431 façades, of which 67 are part of the additional sample collected during the field work performed in this research.

When performing the inspections, the collected data for each façade includes: i) the characteristics of the cladding, namely the colour, the peripheral protection, the type of coating, and the type of finishing; ii) the characteristics of the surroundings, such as the façades orientation, the exposure to damp, the distance from the sea, the combined action of the rain and wind, and the exposure to pollutants.

As for the anomalies, staining and colour or texture changes are the most common group of anomalies, whereas defects of loss of adhesion are the least common.

5. Degradation models

To process the sample data for the definition of the stochastic methods, degradation models are defined. For that purpose, the methodology created by Gaspar and Brito [10, 11, 12] was applied to the sample analysed. It consists of a simple framework that relates the affected area and importance of each anomaly with the total severity of the degradation present in the façade, expressed in terms of the severity of the degradation, S_w, which is calculated using equation (1).

$$S_w = \frac{E_w}{k} = \frac{\sum(A_n \cdot k_n)}{A \cdot k} \quad \textbf{(1)}$$

Where E_w represents the weighted degradation extension, k represents a multiplying factor that corresponds to the highest level of the condition of the degradation of the affected area, A_n represents the area affected by the anomaly n, k_n represents the multiplication factor for anomalies of type n, and A represents the total area of the façade.

5.1 Degradation curves

The degradation curves allow a graphical representation of the effect of the deterioration and loss of performance of the materials over time (Figure 1). This graphical method is an expeditious way to evaluate the performance of the façades and estimate their service life. For the case of ETICS, the end of the service life occurs when $S_w = 30\%$. When applying the graphical method to the sample, the age for which this value of S_w is reached is 18.5 years. This value e close to the one obtained by Tavares et al. [9] when applying the graphical method to their sample of ETICS façades.

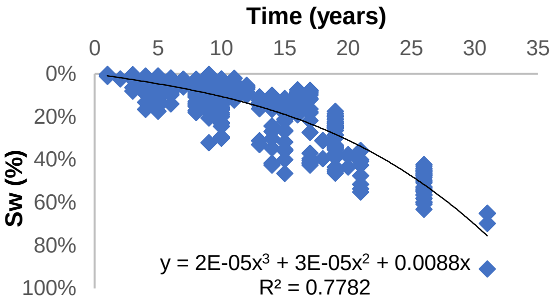

Figure 1 - Degradation curve for the total sample.

6. Stochastic models

The application of deterministic methods to model the evolution of the degradation of buildings does not allow considering the randomness associated to real life phenomena. Therefore, more advanced methods need to be employed, so that more realistic results can be attained, thus providing information that can be used to aid the planning of the inspection and maintenance actions of the façades.

Stochastic methods can then be used to consider the variability associated with the degradation processes, allowing to make a probabilistic analysis of the evolution of the degradation of the construction elements. In the specific case of the age when the end of the service life is reached, deterministic models provide a value for which all the façades must reach the end of their service life. On the contrary, stochastic models provide a value of the age for which it is most probable that the end of service life is reached.

6.1 Logistic regression

Regression models allow estimating the parameters that establish mathematical relationships between dependent and independent or explanatory variables [13]. When the dependent variable is quantitative and the explanatory variables are categorical or numeric, the categorical regression is used. When the dependent variable is nominal dichotomous, the binomial logistic regression is used. If the dependent variable has more than two mutually exclusive categories, the multinomial logistic regression must be applied [14].

The elements of the sample can assume the values "yes" and "no", as to whether they comply with some relevant characteristic for the analysis performed. To check whether one occurrence j $(j = 1, \dots, n)$ of the sample is a "yes" or a "no", the logistic function is used. It assumes the generic form presented in equation (2), where X_i $(i = 1, \dots, p)$ are the explanatory variables and β_j the regression coefficients. The ratio $\hat{\pi}/(1-\hat{\pi})$ is called the likelihood ratio and it represents a measure of the association between the dependent variable and the independent variables.

$$\hat{\pi} = \frac{e^{\beta_0+\beta_1 X_{1j}+\cdots+\beta_p X_{pj}}}{1+e^{\beta_0+\beta_1 X_{1j}+\cdots+\beta_p X_{pj}}} \quad \textbf{(2)}$$

The regression coefficients must be estimated, so that the model can be built. To do that, equation (3) is used, and iterated multiple times with a computational algorithm, until a stop criterion is reached. After this model adjustment has taken place, its statistical significance needs to be validated, using the likelihood ratio test. This test reveals the quality of the fit of the model to the sample.

$$LL = \sum_{j=1}^{n}\left\{y_j Ln\left(\hat{\pi}_j\right) - \left(n_j - y_j\right)Ln\left(1-\hat{\pi}_j\right)\right\} \tag{3}$$

Usually, the Pearson χ^2 and Deviance tests are used to evaluate the model's goodness-of-fit. The significance of the model coefficients is also tested, via the Wald test [15]. These models use the pseudo-R^2 to evaluate the goodness-of-fit. Although there are multiple variants of this coefficient, in the context of the logistic regression, the Cox and Snell [16], Nagelkerke [17] and McFadden [18] pseudo-R^2 are considered. After finishing the models, their classification table can be used to analyse the model´s accuracy of classification.

6.1.1. Application to the service life prediction

This study applies the software SPSS (Statistical Package for Social Sciences) to build a model for the base scenario, which only considers the effect of the age in the durability of the façades, and an additional scenario, which considers the effect of the age and additional explanatory variables.

When determining the probability of the façades being in a given degradation condition as a function of their age, characteristics, and environmental conditions to which they are subjected, equations (4) and (5) are used. Figure 2 presents the instants when the probability of transition between consecutive degradation states is maximum.

$$P(Y = \text{"}Reference\ class\text{"}|X) = \frac{1}{1+e^{B_{10}+B_{11}\cdot X_1+\cdots+B_{1p}\cdot X_p}+\cdots+e^{B_{n0}+B_{n1}\cdot X_1+\cdots+B_{np}\cdot X_p}} \tag{4}$$

$$P(Y = \text{"}Class\ i\text{"}|X) = \frac{e^{B_{i0}+B_{i1}\cdot X_1+\cdots+B_{ip}\cdot X_p}}{1+e^{B_{10}+B_{11}\cdot X_1+\cdots+B_{1p}\cdot X_p}+\cdots+e^{B_{n0}+B_{n1}\cdot X_1+\cdots+B_{np}\cdot X_p}} \tag{5}$$

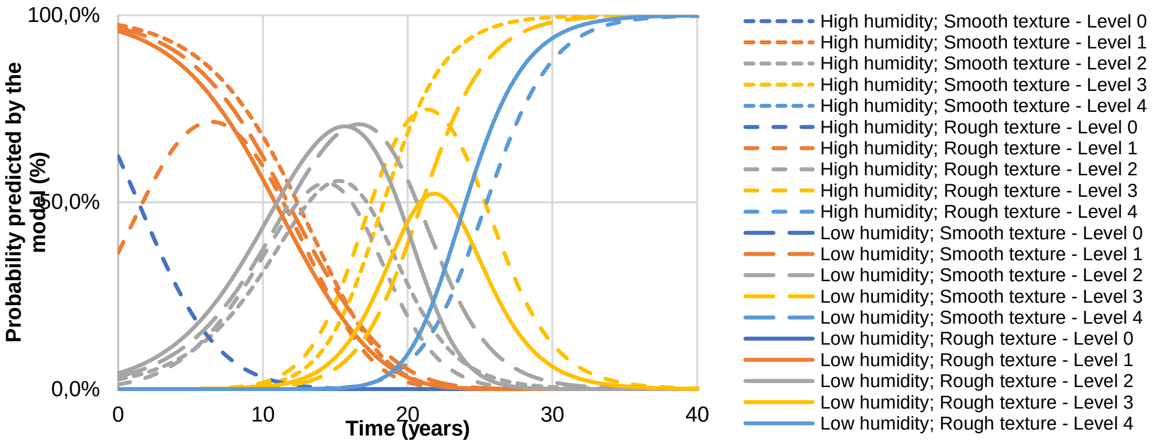

Figure 2 - Probabilistic distribution of the degradation, as a function of the age, texture, and humidity exposure of the claddings of the sample.

To compare the service life obtained by the graphical method with the results obtained using the logistic regression, a model based on the binomial logistic regression is presented, considering just the influence of the age of the façades in the evolution of the degradation. Figure 3 shows the different values of age for which the probability of reaching the end of the service life has different values. The age for which the probability of ETICS reaching the end of service life is 50% is 18 years. When that probability is 90%, the age of ETICS is 23 years. Table 1 allows comparing the ages obtained for the different models developed during this study.

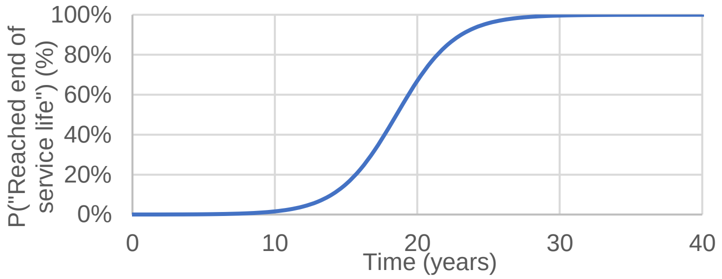

Figure 3 - Probability distribution of reaching the end of the service life, as a function of the age of the façades.

Table 1 - Age for which the façades reach the end of the service life, according to the models defined by the binomial logistic regression.

Scenario	Attribute value	Age for P("Reach end of SL")=50% (years)	Age for P("Reach end of SL")=90% (years)
Base model	-	18,5	23,5
Orientation	N+NE	18	23
	E+SE	20	24
	S+SW	19,5	24
	W+NW	18	23
Distance to sea	Inferior to 5 km	18	23
	Superior to 5 km	19	24
Combined action of rain and wind	High	18,5	23
	Low	21,5	26
Exposure to pollutants	High	16,5	21
	Low	20	23
Type of coating	Traditional	18,5	23
	Reinforced	21	26
	Ceramic	53	58
Combined action of rain and wind + Exposure to pollutants	High wind; High pollutants	16	20
	High wind; Low pollutants	20	23
	Low wind; High pollutants	20	24
	Low wind; Low pollutants	24	27

6.2 Markov chains

The evolution of the degradation of an element can be seen as a continuous process, which can be described by the successive transitions between consecutive states of degradation [19]. The continuous time Markov chains allow defining models that can be used to estimate the probability of the performance of a material in each moment, based on its current performance level and its age, without needing to know the previous states of the element analysed, in a property known as "loss of memory".

To create Markov chains-based models, a transition matrix, Q, must be defined, such that the probabilities of the transition between states are included in that matrix. After knowing the transition rates, it is possible to solve the differential equations system in equation (6), thus calculating the probability of permanence or transition between different states. The transition rates are obtained by applying equation (7), where n_{ij} represents the number of façades that transit from the state i to the state j and $\sum \Delta t_i$ represents the sum of the time intervals between inspections of the elements that have i as the beginning state.

The model needs to be optimized, to be effective in the service life prediction of ETICS. Similarly to the case of the logistic regression, the likelihood is considered. Using equation (8), the likelihood can be estimated [20, 21] Using equation (9), it is possible to determine the mean time of permanence in each condition of degradation.

$$\frac{d}{dt} P(\Delta t) = Q \cdot P(\Delta t) \qquad \textbf{(6)}$$

$$\theta_i = Q_{ij} = \frac{n_{ij}}{\sum \Delta t_i} \qquad \textbf{(7)}$$

$$L = \prod_{i=1}^{n} \prod_{j=1}^{m} P_{ij} \qquad \textbf{(8)}$$

$$T_i = \frac{1}{q_{ij}} \qquad \textbf{(9)}$$

6.2.1. Application to the service life prediction

The Markov chains models presented in this study were defined using the MATLAB software. A base scenario, considering only the effect of the age of the façades in the evolution of their durability, and an additional scenario, considering the effect of additional explanatory variables, were defined. As for the logistic regression, the Markov chains consider the base scenario when determining the age for which the probability of reaching the end of service life is 50% and 90%, with the values of 23 and 51 years, respectively (Figure 4).

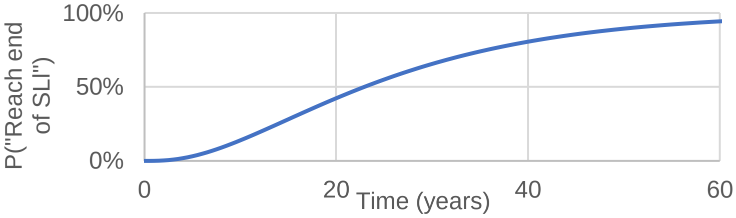

Figure 4 - Probability distribution for reaching the end of the service life, as a function of the age of the façades.

Figures 5 and 6 shows the probability of ETICS having a given degradation condition as a function of their age, characteristics, and environmental conditions, and it is possible to determine the instants when the probability of transition between consecutive degradation states is maximum.

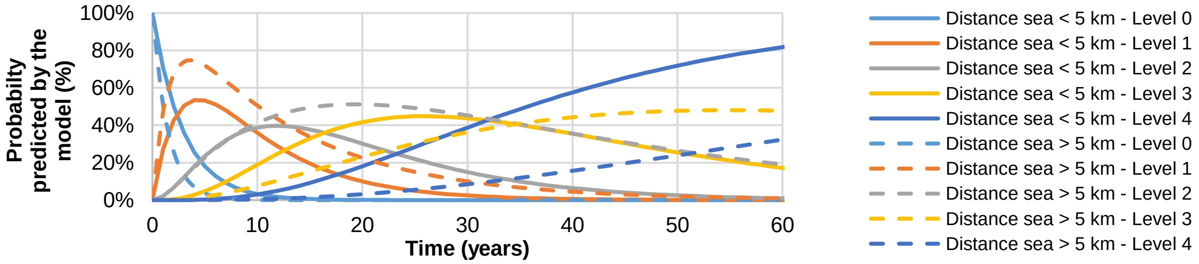

Figure 5 - Probability distribution of the degradation, as a function of the distance of the façades from the sea.

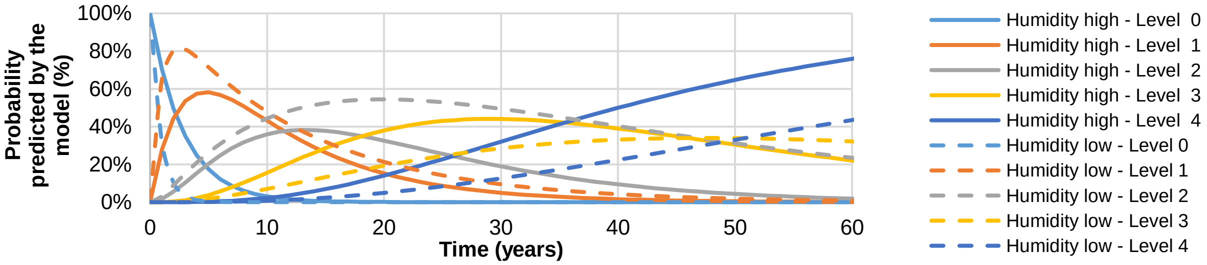

Figure 6 - Probability distribution of the degradation, as a function of the humidity exposure of the façades.

Table 2 allows comparing the probability of ETICS reaching the end of their service life, according to their characteristics, based on the models created using Markov chains.

Table 2 - Probability of ETICS reaching the end of their service life, according to Markov chains.

Scenario	Attribute value	P("Reach the end of SL")=50% (years)	P("Reach the end of SL")=90% (years)
Base model	-	23	51
Orientation	N+NE	22	48
	E+SE	24	55
	S+SW	26	57
	W+NW	22	49
Distance to sea	Lower than 5 km	18	37
	Higher than 5 km	34	79
Exposure to humidity	High	20	42
	Low	36	Superior to 80
Combined action of rain and wind	High	23	50
	Low	28	66
Exposure to pollutants	High	26	57
	Low	22	47
Type of coating	Traditional	23	49
	Reinforced	36	Superior to 80
	Ceramic	72	Superior to 80
Colour	White	20	45
	Light colours	21	45
	Dark colours	Superior to 80	Superior to 80
Type of finishing	Smooth	30	71
	Rough	23	49
Peripheral protection	High starting profile	58	Superior to 80
	Wainscot	19	41
	Other	31	77

6.3 Comparison of the models

During the application of the additional multinomial model, it is concluded that the façades with lower exposure to damp tend to have lower levels of degradation than the façades with higher exposure, which makes physical sense, since the presence of water is a catalyst for the degradation. As for the texture, the rough façades have higher probability of belonging to higher levels of degradation, since the rough texture tends to catch more water and debris, thus potentiating the degradation phenomena.

The base binomial model indicates the age of 18 years for the transition between levels 2 and 3 of degradation, which corresponds to the end of service life of ETICS, for $S_w = 30\%$.

In Markov chains, the same transition between levels 2 and 3 occurs at the age of 23 years, which corresponds to the age with the higher probability of reaching the end of the service life. When exposure to damp is low and when the distance from the sea is higher than 5 km, the façades tend to maintain the level 2 during a longer period of time.

Finally, regarding the value obtained by the graphical method, the estimated service life is very close to the one determined by the logistic regression. In the case of the Markov chains, the value has almost 5 years of difference, but that discrepancy can be explained by the fact that Markov chains tend to result in older ages for reaching the service life.

7. Conclusions

In this study, the evolution of the durability of ETICS systems is analysed, using two different stochastic methods, and comparing the results with the existing literature for this element. The age of the façades, the characteristics of the materials and the characteristics of the surroundings were considered, reaching some conclusions regarding the age for which the probability of reaching the end of the ETICS' service life is maximum.

After concluding the field work, the resulting sample provided adequate coverage of the attributes considered in the model. However, there are still some attributes that can be further improved in terms of their representativity in the sample. This is a gradual process and requires specific combinations of attributes to be present in the façades being inspected.

The graphical method is an expeditious approach to the calculation of the service life because it is very simple to apply. However, this method does not consider the probabilistic aspects of the degradation and the variability associated to the conditions of service, to which the façades are submitted. On the other hand, the application of the stochastic models is considerably more complex but has the advantage of producing more realistic results, because the probabilistic effects are considered in the model. Regarding the values obtained for the service life in this study, they are aligned with various works available in the literature [22, 23, 24, 25].

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