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Service life prediction of paint coating of Algiers building envelopes by applying a multiple linear regression analysis

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Abstract
The durability of a building is strongly related to the service life of its various components, including the coatings of its envelope. The paint on the building envelope is the first protective layer exposed to the harmful effects of the climate and environmental conditions. These effects are manifested over time by degradations such as color change, cracking, peeling, etc. In this contribution, a predictive model of the service life of paints coating, applied on cementitious materials of building envelopes located in Algiers, is proposed. The model is based on a multiple linear regression analysis of descriptive results of visual investigations combined with in situ tests on the degradation of the facade paints of 45 buildings sample, selected according to their age, their distance to the coast as well as their orientation with respect to the climatic factor exposures. The proposed predictive model satisfactorily reproduces the field results.
Keywords: Paint coating; Degradation; Service life prediction.

1. Introduction

In recent decades, the durability of building materials and components has received considerable attention in the construction industry. As a reminder, durability is defined as the ability of a building or its parts to perform its required function for a specified period under the influence of the agents expected in service (ISO 15686-1, 2000). Despite the fact that the materials used today have become more durable, there are still certain environmental and climatic agents that primarily affect the initial performance characteristics of each building element (BS 7543, 2003). Among the building materials, facade cladding is obviously the most exposed to these various degradation agents, such as rain, wind, solar radiation and pollutant emissions, etc. (E Bauer et al., 2020; Riahinezhad et al., 2021; Souza et al., 2018; Amen, 2021; Aziz Amen, 2022; Amen et al., 2023; Amen & Nia, 2020). These factors cause various anomalies to appear on the exterior cladding, gradually affecting over time the façade's aesthetics, and especially its functional performance, hence the importance of monitoring the condition of building façades throughout their life cycle. In fact, monitoring the performance of a material over time describes a statistical distribution of the decline of this characteristic, and must therefore be addressed by appropriate methods. In practice, the service life of building components can be assessed by building inspection. As many buildings as necessary should be included in the study, using appropriate statistical sampling methods.

Over the most exterior wall coatings, the use of paint is in practice since a long time, not only for its decorative characteristics but also to its several advantages relative to other coating materials that lead to a lower global cost (Folorunso and Ahmad, 2013). Despite these advantages, there is a considerable chance that paint finishes will not achieve the expected performance. This may be due to the different factors that control this process, like the use of adequate supports, the quality of design and execution, the environmental exposure conditions, the conditions of use and the maintenance frequency (Magos et al., 2016; Silva et al., 2015). After a detailed examination of numerous scientific reports, it has been found that there is no information on the extent of the permissible risk for paint coatings applied to exterior facades located in different regions, hence the importance of developing methodologies and tools predicting the service life of the paint coating. The main objective of any service life prediction of building material, system or component is to estimate and evaluate its capacity to satisfactorily perform its operations throughout the service life of the building or throughout the period considered reasonable for maintenance. Previous studies have established the relationship between the severity and different causes of degradation (Elton Bauer et al., 2020; Uchaeva and Loganina, 2018). All these methods require the quantification of each degradation detected at surface coating. However, there are many approaches for durability design and modeling of structural deterioration and service life exist. These methods are generally divided into three categories: (1) service life estimation methods and durability design standards, (2) maintenance optimization methods, and (3) time-variant structural reliability. Concerning the first method, the service life prediction can be obtained by: (i) deterministic models (regression analysis: simple nonlinear regression; multiple linear regression; and multiple nonlinear regression); (ii) stochastic models (logistic regression and Markov chains); (iii) computational methods (artificial neural networks and fuzzy systems); (iv) factorial methods (classical and probabilistic approach) (Silva et al., 2016). Among these methods, it appears that the multiple linear analysis gives relatively good results for the service life prediction of external wall painting (Silva et al., 2015,).

Chai et al., (2015)developed a statistical methodology for the service life prediction of exterior wall painting. This research is based on the collection of field data through inspection of degradation level of 220 painted coatings that were distributed in 160 buildings of different construction types. In this work, a mathematical model has been established using multiple linear regression analysis, which lets to express the coating deterioration over time as a function of various degradation factors. The obtained model is based on the visual inspection and anomalies quantification. The authors concluded from this study that the most influenced factors on the degradation severity of paint coating is, the age, the distance from the sea, façade orientation and wind-rain action. In addition, according to the simultaneous analysis of the degradation factors, it has been revealed that 83% of the degradation can be explained by just three independent variables through a multiple linear model, namely: age, façade orientation and distance from the sea. In the other hand, Silva et al., (2015)studied the service life prediction of different paint surfaces using three statistical tools are used: i) simple regression analysis (also referred to as graphical method); ii) multiple linear regression analysis (MLR); iii) and artificial neural networks (ANNs). Using these three methods, it appears that the multiple linear regression analysis gives adequate paint coating life predictions, an estimated mean life of 8.5 years is obtained with a standard deviation of 0.54 years. In addition, this method makes it possible to identify the most relevant variables in explaining degradation phenomena.

The method of prediction service life proposed in the present work is established through the evolution of the degradation state of 45 external wall painting inspected in the Algiers city, in Algeria. The overall degradation level of the paint coating is performed using a numerical index, called degradation severity (Sw). The influence of three degradation factors on the paint coating performance, over time, is also assessed during the inspections, namely, the age, distance from the sea, and façade orientation. Multiple linear regression analysis is used in order to identify the most accurate model to predict the service life of painted coatings on exterior walls of buildings.

2. Materials and Methods

2.1 Investigation sites

In the present investigation, forty-five (45) investigation sites of residential buildings located in 22 municipalities of the city of Algiers were selected for the prediction of the service life of exterior wall painting (see figure 1). Based on the literature review, the three independent variables deemed most influential were selected: age, distance from the sea and façade orientation. Concerning the age of the sample analyzed, the most recent and oldest case studies are 3 and 42 years old respectively (see Table 1). In order to assess the effect of distance from the sea on paint coating degradation, three categories are selected, each comprising a third of the buildings. The categories are distinguished by their distance to the coastal zone: (a) more than 5 km; (b) between 1 and 5 km; and (c) less than 1 km. Facade orientation was obtained using the Google Maps application, with eight main solar orientations considered: North, East, South, West, North/East, South/East, South/West and North/West. Each sample number associated with facade solar orientation is shown in Table 2.

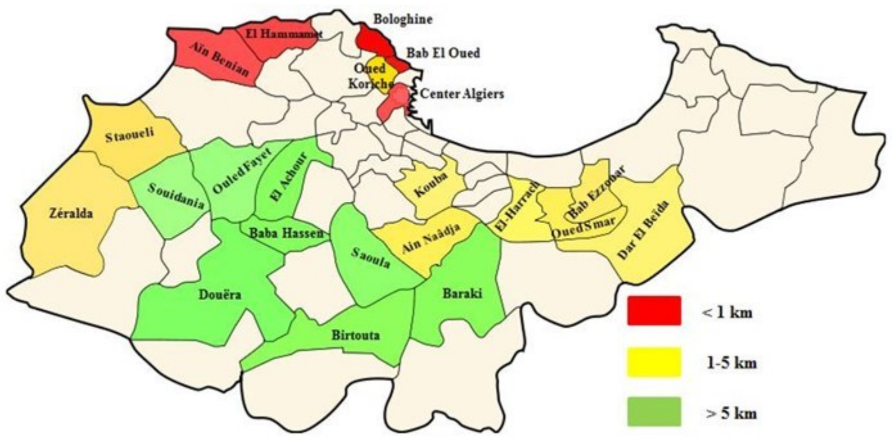

Figure 1. Localization of Algiers inspected building and their distance from the sea.

Table 2. Characterization and distribution of the study sample according to coating ages.

Coating age (years)	Percent of sample (%)
Under 10	35.56
Between 11 and 20	35.56
Above 21	28.88

Table 3. Samples amount for each orientation façades.

Solar orientations	Sample amount (%)
North	13.33
East	8.89
West	24.44
South	24.44
North/East	8.89
South/East	8.89
South/West	6.66
North/West	4.44

2.2 Description of the field work sample

As part of the fieldwork, data was collected for each building inspected, by means of (i) photographic recording of the facade; (ii) measurement of facade dimensions; (iii) collection of information on the first and last paint application intervention from the building owner (in our case the OPGI, Office de Promotion et de Gestion Immobilière); (iv) on-site interpretation of paint surface texture and substrate surface preparation, and (v) compilation of paint inspection records for each facade. Measured facade widths and heights were used to scale the facade image. The "age" variable is considered to be the period of time between the date of the last painting (e.g. general repair, with partial or total replacement of the cladding) and the date of the inspection. According to OPGI's technical documents, acrylic paint is used in all the surface coatings inspected. What's more, most of the paints on the façades inspected are applied directly to a cement mortar substrate covering the masonry. During the investigations, various anomalies are identified on the paint surfaces, amongst others aesthetical, adhesion loss, cracking and defects in openings, etc. However, the degradation of the studied coating generally leads not only to the loss of their aesthetic performance but also compromises their protective function. The different levels of degradation are defined in terms of type of anomalies and their intensity, regardless of the extent of the pathological manifestation. In the present study, this hypothesis (supported by several international standards) is adopted. Based on these documents and to Chai et al. 2015 study, four main anomalies that affect the service life of paint coatings are considered in this paper, namely: color change (CC), chalking (CG), cracking (CK), and loss of adherence (LA) (Chai et al., 2015). Theses degradation phenomena and their ranking are clearly described in the following sections.

2.3 Evolution of the degradation severity of painted surfaces

The overall degradation generally formed at each façade coating may be estimated by a mathematical expression which translates the qualitative and quantitative data obtained through on-site inspections work. Gaspar and de Brito proposed a numerical index in order to translate the global degradation rate occurring on the building component or cladding system, based on the anomalies observed, their severity and extent (Bordalo et al., 2011; Gaspar and de Brito, 2008). This numerical index, named degradation severity (Sw), described by Eq. (1), provides an evaluation of the global degradation of the cladding though the ratio between the degraded area (weighted according to the severity of the anomalies observed) and a reference area that is equal to the total claddings' area with the highest possible degradation level.

$$\boldsymbol{Sw} = \frac{\sum(\boldsymbol{A_n} \times \boldsymbol{k_n} \times \boldsymbol{k_{a,n}})}{\boldsymbol{At} \times \boldsymbol{k}} \quad (1)$$

where: *Sw* is the degradation severity of the coating, expressed as a percentage (%); k_n is the multiplying factor of anomalies n, as a function of their degradation level, within the range $k_n = \{0, 1, 2, 3, 4\}$; $k_{a,n}$ is weighting factor corresponding to the relative weight of the anomaly detected ($k_{a,n} \in R^+$); $k_{a,n} = 1$ by default; A_n represent the area of coating affected by an anomaly n, in m^2; *A* is façade area, in m^2; and *k is* multiplying factor corresponding to the highest degradation level of a coating of area A. It can be noted that the values of multiplying factor (k) are evaluated conforming to the ISO 15686-7 (2017) standard, which establishes the effect of degradation on the service life of the building (ISO 15686-7: 2017). For this purpose, five conditions (A, B, C, D, E) are associated for k values, for each group of anomalies.

2.4 Multiple linear regression analysis

Multiple linear regression analysis (MLR) is one of the most widely used techniques that can be estimate the relationship between two or more independent variables and one dependent variable. However, for any application of MLR in prediction models, the main objective is to clarify a given reality and try to anticipate the role of a dependent variable (Sw) as a function of the independent variables. The conventional mathematical formulation used in multiple linear regression analysis is shown in Equation (2).

$$Y_i = b_0 + b_1X_1 + b_2X_2 + \cdots + b_iX_i + \varepsilon_i = \sum_{i=1}^{p} b_iX_i + \varepsilon_i \quad (2)$$

where Y is the dependent variable (Sw), Xi, (i=1,2…, p) are the independent variables; bi, (i=1,2…,p) are the parameters of the model and ε_i is the model random error. The results of the multiple regression analysis were obtained with the help of SPSS software and Excel Microsoft, which allows the adjustment of nonlinear functions directly. There are several methods that can be select the suitable model able to describe the relationship between the degradation severity (Sw) and the independent variables including in the multiple linear regression analysis, like: Enter, stepwise, backward, forward, …, etc. In this study, the Enter technique is adopted to analyze the results of the regression model. This procedure analysis is considered as default method for the multiple linear regression analysis which means that all variables are forced to be in the model. Thus, some basic assumptions are verified after the model is build, indeed, the model residual and multicollinearity between different independents variables are analyzed.

3. Results and discussions

3.1 Quantification of degradation factors

The evolution of the degradation of the paint coating over time was first treated using a graphical procedure and a simple linear line, the abscissa and ordinate of which measure the variables "age" and "severity of degradation" respectively. This graphical representation allows determining the reference service life (RSL) by the intersection of the average degradation curve and the maximum acceptable degradation level corresponding to the end of the paint coating's service life. However, the specification of this theoretical lifetime limit is rather difficult, as new performance requirements are constantly being demanded. These requirements force manufacturers to invest constantly in order to delay the degradation trend affecting exterior wall coatings. However, most studies on the subject consider nowadays that the minimum accepted level of performance is the stage of deterioration that limits one or more essential functional requirements. This limit corresponding approximately to a performance level of around 20 % is generally considered for paint coating, although it can vary significantly depending on the construction materials studied (Magos et al., 2016). Once this limit performance is defined, the estimate of the RSL of the painted surfaces is obtained by intersecting the degradation curve with the horizontal line that represents the minimum acceptable performance level. According to this method, an average RSL of 20 years is obtained for the coating of 45 paints, which corresponds to twice the RSL values obtained by (Chai et al., 2015), around 10 years. Furthermore, each category of independent variables is associated with a value representing the ratio between the estimated lifetime as a function of each coating characteristic and the reference lifetime of 20.3 years. Table 3 summarizes the values obtained in this study.

In terms of building location, the results indicate clearly that the estimated service life decrease with getting closer to the coast zone, low values are obtained for the distance from the sea lower than 1 km. As expected, this lower value obtained the coastal zone mainly due to the exposure of the faint surfaces to the several degradation agents, like: moisture and sea spray salinity, which lead to the crystallization of salts on the surface and between the substrate and Paint coating. Concerning the façade orientation, it can be seen that the façades facing east, south and east/south present lower estimated service life compared to others orientations. This is mainly because to the to the solar and wind/rain actions which reduce the service life of external wall painting.

Table 4. Numerical quantification of the independent variables.

Characteristics	Independent variables	% of cases	Reference service life (Years)	Estimated service life (years)	Ratio between estimated service life and reference service life	R^2 of degradation curves
Distance from the sea	< 1 km	33.33	20.3	19.8	0.975	0.0477
	1 – 5 km	33.33		21.1	1.039	0.3684
	> 5 km	33.33		20	0.985	0.768
Façade orientation	North	13.33		31.6	1.556	0.2984
	East	8.89		19.7	0.970	0.5239
	South	24.44		18.3	0.901	0.3
	West	24.44		27.6	1.359	0.4146
	North/East	8.89		24	1.182	0.1

South/East	8.89	19.5	0.960	0.3847
South/West	6.66	23.3	1.147	0.8909
North/West	4.44	24	1.182	1

3.2 Service life prediction model

The mathematical formulation given by the Eq. (3) is obtained by multiple linear regression analysis, using the numerical quantification of the independent variables summarized in Table 4. The numerical quantification of the variables included in the model presents a physical meaning, and the interpretation of the results is coherent. As expected, this model presents a very strong correlation between degradation severity (Sw) and different independent variable, deemed appropriate to model the durability of painted surfaces.

$$S_w = -0.22 + 0.003\,(\text{Coating Age}) + 0.3\,(\text{Distance from the sea}) + 0.02\,(\text{Façades orientations}) \quad (3)$$

Using this equation, it is possible to calculate the estimated service life (ESL) for each case study within the sample, assuming a maximum degradation severity of 20%, as indicated in the following expression, where age is now the dependent variable.

$$ESL = \frac{(0.2+0.22-0.3\,Distance\ from\ the\ sea-0.02\,Façades\ orientations)}{0.003} \quad (4)$$

Once the variables "distance from the sea" and "façade orientation" are converted to numbers (Table 3), it can be estimate the expected age for a degradation severity of 20%. The reference service life obtained by this multiple linear regression model is thus the average of all the ESL values of each observation, and a standard deviation of the reference service life can also be determined. Indeed, an average estimated service life of 29.9 years is achieved, with a standard deviation of 3.26 years, this results is higher than the value obtained by the graphical method (20.3 years) but still consistent with the empirical knowledge related with the durability of painted surfaces.

3.3. Validation of the assumptions of the model

In this study, the validation of the assumptions of obtained model was done by the ANOVA test, VIF and residual analysis The ANOVA analysis for the multiple linear regression model obtained for painted surfaces is reported in table 5. The sum of the square is defined as the sum square deviations associated with each of the variation sources. this variation is explained by the independent variable and with the initial or total residual variation. The degrees of freedom are systematically related to the amount of data available for statistical analysis, 45 in this work. In the other hand, the ration between the sum of the square and the corresponding degree of freedom give mean square values. In order to evaluate the explanation capacity of the model, F (F-statistic) is used. However, the null hypothesis (B=0) if F is higher than a critical value, i.e. the model has a statistically significant explanation capacity; the critical value of F is given in the Fisher–Snedecor tables, which relate the numerator and the denominator degrees of freedom for a given level of significance; in this work, for a 5% level of significance, 3 numerator degrees of freedom and 41 denominator degrees of freedom, the critical value of F was 0.0002, significantly lower than the value obtained (8.83). Finally, sig. or significance analyzed the probability of rejecting the null hypothesis when it is in fact true; in this case, the significance value obtained is 0.000, which is less than 5% (admitted p-value) and therefore it can be concluded that the independent variables under consideration were indeed the cause of the dependent variable.

Table 5. ANOVA table of multiple linear regression model obtained for inspected painted surfaces

Model	Sum of squares	Degree of freedom	Mean square	F	Sig.
Regression	0,0517	3	0,017	8.83	0.000
Residual	0,0830	41	0,002		
Total	0,1347	44			

Table 6 present the diagnostic of collinearity for the independent variables included in the model. The results of VIF (variance inflation factor) show that there is no risk of multicollinearity between different variables in the model (VIF < 5). The significance values for the regression coefficients are always less than 5 % (adopted significance level) indicating that all the variables included are statistically significant.

Table 6. VIF (variance inflation factor) values for each explanatory variable of the proposed model

Independent variable	VIF
Age	1.275
Distance from the sea	1.111
Façade orientation	1.310

The analysis of the residuals is performed in order to estimate the difference between the predicted and observed values of degradation severity, which is an informative tool to examine the adequacy of the regression model to the observed data. A graphical method is used in this study in order to analyze the variance of the residuals versus the values of the independent variable "age, distance from the sea and façade orientation" (Figure. 2). Figure 2 shows that for all independent variables, the expected value of the residuals is close to zero, i.e. E(ej) ≈ 0. However, in terms of variance the width of the cloud of points is not completely uniform. After 10 years there are various points with a high residual compared with the remaining sample. This is mainly due to the presence of atypical points, also called outliers, which are not representative of the sample.

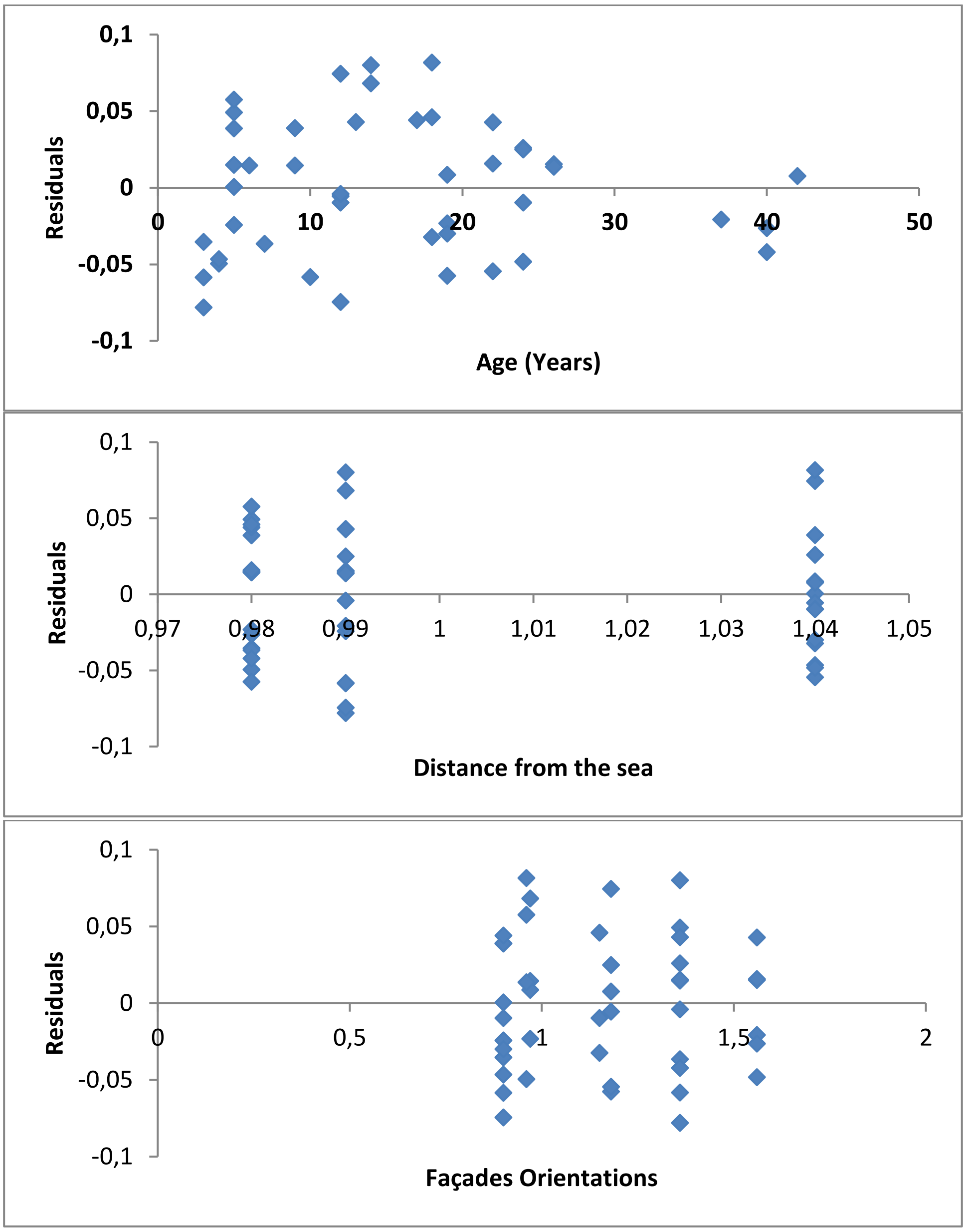

Figure 2. Residuals versus different independent variable

4. Conclusions

This study presents a methodology to predict the service life of Algiers external wall painting by applying a multiple linear regression analysis. This methodology is applied to 45 paints surfaces of residential building façades, in Algeria. The result of this work indicate clearly that a lower estimated service life was obtained for building located at the coastal zone and façades facing east, south and east/south. Moreover, the multiple nonlinear regression model leads to the best overall results according to the statistical indicators analyzed. Indeed, the service life values estimated with this model was found very close to reality, for which an average estimated service life of 29.9 ± 3.26 years is achieved. This result is higher than the value obtained by the former graphical method (20.3 years).

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Conflict of Interests
The authors declare no conflict of interest.

References
Amen, M. A. (2021). The Assessment of Cities Physical Complexity through Urban Energy Consumption. Civil Engineering and Architecture, 9(7), 2517–2527. https://doi.org/10.13189/cea.2021.090735

Aziz Amen, M. (2022). The effects of buildings' physical characteristics on urban network centrality. Ain Shams Engineering Journal, 13(6), 101765. https://doi.org/10.1016/j.asej.2022.101765

Amen, M. A., Afara, A., & Nia, H. A. (2023). Exploring the Link between Street Layout Centrality and Walkability for Sustainable Tourism in Historical Urban Areas. Urban Science, 7(2), 67. https://doi.org/10.3390/urbansci7020067

Amen, M. A., & Nia, H. A. (2020). The Effect of Centrality Values in Urban Gentrification Development: A Case Study of Erbil City. Civil Engineering and Architecture, 8(5), 916–928. https://doi.org/10.13189/cea.2020.080519

Bauer, E., De Souza, J.S., Piazzarollo, C.B., (2020). Application of the degradation measurement method in the study of facade service life, in: Building Pathology, Durability and Service Life. Springer, 105–119.

Bauer, E., Piazzarollo, C.B., de Souza, J.S., dos Santos, D.G., (2020). Relative importance of pathologies in the severity of facade degradation. J. Build. Pathol. Rehabil. 5, 1–10.

Bordalo, R., de Brito, J., Gaspar, P.L., Silva, A., (2011). Service life prediction modelling of adhesive ceramic tiling systems. Build. Res. Inf. 39, 66–78.

BS 7543, (2003). Guide to durability of buildings and building elements, products and components. Br. Stand. Inst. 3, 28.

Chai, C., De Brito, J., Gaspar, P.L., Silva, A., (2015). Statistical modelling of the service life prediction of painted surfaces. Int. J. Strateg. Prop. Manag. 19, 173–185.

Folorunso, C.O., Ahmad, M.H., 2013. Performance and resistance of paint used as exterior finish in salt laden environment. Struct. Surv.

Gaspar, P.L., de Brito, J., (2008). Quantifying environmental effects on cement-rendered facades: A comparison between different degradation indicators. Build. Environ. 43, 1818–1828.

ISO 15686-1, (2000). Buildings and constructed assets - Service life planning-Part 1: General principles and framework. BSI Stand. Publ.

ISO 15686-7:, (2017). Buildings and constructed assets- Service life planning-Part 7: Performance evaluation for feedback of service life data from practice. Int. Stand. Organ.

Magos, M., de Brito, J., Gaspar, P.L., Silva, A., (2016). Application of the factor method to the prediction of the service life of external paint finishes on façades. Mater. Struct. 49, 5209–5225.

Riahinezhad, M., Hallman, M., Masson, J.F., (2021). Critical review of polymeric building envelope materials: degradation, durability and service life prediction. Buildings 11, 299.

Silva, A., de Brito, J., Gaspar, P.L., (2016). Comparative analysis of service life prediction methods applied to rendered façades. Mater. Struct. 49, 4893–4910.

Silva, A., Gaspar, P., de Brito, J., (2015). Evaluation of the service life of external painted surfaces applying statistical tools, in: 1st International Symposium on Building Pathology (ISBP 2015). Porto, Portugal.

Souza, J., Silva, A., de Brito, J., Bauer, E., (2018). Analysis of the influencing factors of external wall ceramic claddings' service life using regression techniques. Eng. Fail. Anal. 83, 141–155.

Uchaeva, T. V, Loganina, V.I., (2018). Analysis of the risk at the finishing of the building products and construction of paint compositions. Case Stud. Constr. Mater. 8, 213–216.