International Journal of Strategic Property Management
ISSN: 1648-715X / eISSN: 1648-9179
2018 Volume 22 Issue 3: 204–222
https://doi.org/10.3846/ijspm.2018.1546

APPLICATION OF THE FACTOR METHOD TO THE SERVICE LIFE PREDICTION OF ETICS

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Received 23 August 2016; accepted 3 October 2017

Abstract. This study intends to develop a methodology for service life prediction of ETICS (External Thermal Insulation Composite System), based on the factor method. The methodology adopted is based on data collected during visual inspections of buildings under current conditions of occupation and exposure, contemplating the degradation mechanisms and the characteristics of ETICS. This research can also provide a suitable tool to aid the planning, implementation and rational use of building management systems in several ways, namely: i) improvement of the materials' performance, based on the optimization of maintenance actions, use of resources and maintenance costs; ii) selection of the best constructive solution, based on the knowledge of the evolution of degradation of ETICS, according to their characteristics; iii) analysis of the economic and environmental impacts of buildings during their life cycle, based on the knowledge of the number of replacements required during this period of time.

Keywords: ETICS, service life, durability, visual inspections, factor method.

Introduction

ETICS (External Thermal Insulation Composite Systems) were initially designed with the objective of reducing the energy consumption and the consequent economic impacts of buildings. In a Europe deeply devastated by the 2nd World War, the economic crisis and later on the oil crisis led to an increase in the fuels and refined products costs, thus increasing the demand for new solutions that mitigate the high costs of heating and cooling the buildings while allowing a more rational management of the scarce resources (Fernandes, de Brito, & Cruz, 2016b).

According to Barreira and Freitas (2013), during the energy crisis of the late 60s and early 70s, the interest in exterior thermal insulation gradually increased. Thus, ETICS became a popular solution among the construction companies, due to the emerging awareness regarding the reduction of the energy consumption. These systems began to be used almost exclusively in commercial buildings, being gradually applied over the years as a cladding solution in residential buildings. Nowadays, this system is applied in external walls of new or refurbished buildings in order to improve their thermal performance, namely through: i) the reduction of external walls' thickness – the characteristics and configuration of the thermal insulation system of the building envelope should be defined according to the outside environmental conditions as well the indoor thermal comfort requirements (Ucar & Balo, 2010); a study performed by Theodosiou and Papadopoulos (2008), comparing different insulation solutions, reveals that the ETICS systems (with a solution composed by a single brick wall with a thickness of 21 cm) allows reducing the required heating power by around 21% when compared to the most common type of insulation configuration (double brick wall, with a thickness of 30 cm); ii) the correction of thermal bridges, also preventing the moisture condensation; ii) the active contribution to the conservation of natural resources by increasing the insulation of buildings, reducing the energy losses through the substantial reduction of heating and air conditioning costs (Kolaitis et al., 2013; Amaro, Saraiva, de Brito, & Flores-Colen, 2014; Barreira & Freitas, 2014; Fernandes, de Brito, & Cruz, 2016a).

Even though the use of ETICS in exterior walls has increased significantly in recent years, there still exists a lack of knowledge concerning the durability of these systems (Silva & Falorca, 2009). Moreover, among the various advantages inherent to these insulation composite systems (e.g. thermal advantages and ease of application), the economic benefits that can contribute to an increase of

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its application stand out. Considering this aspect and the growing interest in this type of systems, these materials, their performance and their intrinsic characteristics must be carefully analysed.

ETICS are a system composed of a set of compatible components. These solutions should have a well-planned integration in the façades, fulfilling all the design and detailing requirements (Fernandes et al., 2016a). This cladding system comprises the following layers: the thermal insulation material (boards of expanded polystyrene – EPS, extruded polystyrene – XPS, mineral wool, among others) and the necessary components and specified reinforcements (glue and/or mechanical fastening devices) to ensure the adherence to the substrate; the thin plaster laid in several coats reinforced with a glass fibber mesh (additionally, a primer coat can be applied after this reinforced layer) and, finally, the finishing decorative layer (Collina & Lignola, 2010; EAE, 2011; Amaro, Saraiva, de Brito, & Flores-Colen, 2013; Barreira & Freitas, 2014; Fernandes, de Brito, & Cruz, 2016b).

The main objective of this study is to develop a methodology for service life prediction of ETICS systems using the factor method, as presented by the Architectural Institute of Japan (1993). This methodology is based on the appraisal of the degradation state of 274 claddings in Portugal, which depends on field data collected through visual inspections of buildings. This investigation consists on the classification and quantification of the defects detected in the claddings, the identification of degradation patterns, the modelling of the degradation evolution over time, the factor method application and corresponding evaluation of the degradation factors and, finally, the optimization and validation of the results. The proposed models lead to acceptable and promising results, given the diversity of characteristics and the factors involved in the claddings degradation, although the external thermal insulation systems show great vulnerability to the actual conditions of design, execution and use, which can condition their natural aging process.

This study follows and complement studies carried out by other authors on the durability of ETICS systems, particularly Fernandes et al. (2016a, 2016b) and Ximenes, de Brito, Gaspar, and Silva (2015). This research allows developing new methods to address the durability of constructions and their components, providing tools to aid the planning and implementation of maintenance and life cycle management strategies of ETICS claddings and also ensuring better performances of these systems in their application conditions.

1. Background

According to ISO 15 686 -2 (2012), the service life prediction can be seen as "a generic methodology which, for a particular or any appropriate performance requirement, facilitates a prediction of the service life distribution of a building or its parts for the use in a particular or in any appropriate environment". Therefore, these methods are effective tools to identify the instant in which the element under analysis must be subjected to a maintenance or rehabilitation action, in order to ensure that the building fulfils the performance requirements. This information is extremely useful for the optimization of management strategies with minimum life cycle costs. The degradation process begins as soon the constructions and their elements are built and start to be used (Riley & Cotgrave, 2005; Silva, Gaspar, & de Brito, 2015), thus continuously evolving over time. Taking into account the considerable costs associated with the management, operation and maintenance of the buildings in the different phases of their life cycle, it is fundamental to define methodologies to assess the process of degradation of buildings components, as well as their degradation agents and mechanisms.

Building façades are continuously exposed to external aggressive agents, thus being more vulnerable to degradation (Kus & Nygren, 2002; Silva et al., 2015). The knowledge regarding the characteristics and the behaviour of materials, and their vulnerability when subjected to specific environmental actions is extremely relevant for the definition of sustainable and durable buildings (Wyatt, 2005). Various authors (Desimone & Poppof, 1998; Bordeau, 1999; John, Sjöström, & Agopyan, 2002; Hernández-Moreno, 2011) refer that the adequate selection of materials and the adoption of more durable solutions, promoting a higher service life of buildings and their components, is crucial to achieve a more sustainable construction, thus minimizing the rehabilitation costs, the resources used, the environmental impacts and the possible consequences to users.

Masters and Brandt (1986) refer that the durability of materials and construction elements can be improved based on the knowledge of their service life and through proper and effective selection, use and maintenance, enabling the recognition of the most viable and profitable proposal. ISO 15 686 -1 (2011) defines service life as the period of time, after construction, in which the building and its parts meet or exceed the acceptable minimum requirements of performance established. Often, these requirements are subjective parameters, which are quite variable according to the buildings' context (some users are more demanding than others, and in some situations the availability of funds for maintenance actions leads to a stricter level of demand), because, in addition to the functional aspects, aesthetic criteria must also be considered, depending on the assessment of each individual case (Gaspar & de Brito, 2008). In other cases, the performance requirements can also be objective, evaluating measurable aspects of ETICS systems, namely: the thermal performance of the insulation system and hygrothermal behaviour; the mechanical performance, resistance and stability; air tightness; water tightness; among others.

The Guideline on Durability in Buildings (CSA S478-95, 1995) describes service life as the period of time in which the building or any part of it meet their objectives without unanticipated costs, repairs, interruptions or alterations attributable to maintenance. In this context, several service life prediction models were studied and developed with the purpose of analysing and interpreting the deterioration process and the durability of the constructions and their components.

One of the most recognized methodologies to estimate the service life of construction components is the factor method, which is widely accepted in the scientific community and is characterized by its systematic approach, easy applicability and operability in real projects (Re Cecconi, 2004).

The factor method, initially presented by normative document Principal Guide for Service Life Planning of Buildings proposed by the Architectural Institute of Japan (1993), and later adopted by the ISO 15 686 -8 standard (Building and construction assets – Service life planning – Part 8: reference service life and service-life estimation) from the International Organization for Standardization, allows taking into account all the variables that affect the service life of buildings and their elements. According to ISO 15 686 -8 (2008), this method can be applied at different levels of sophistication, ranging from simple checklist to complex calculations. The standard refers that the level of application of the model depends on the "actual purpose of the estimation, type and quality of available data and models, skill level and type of expertise of the user(s) making the estimation and resources and time available for the calculation". This methodology, admitted as a general framework for service life prediction (Emídio, de Brito, Gaspar, & Silva, 2014; Silva, de Brito, & Gaspar, 2016), allows obtaining an estimated service life based on a reference service life of a component or set of components, expected in current conditions of use, multiplied by different weighting coefficients related to the specific conditions of the element under analysis (Hovde, 2004). These parameters are crucial for the durability and performance of claddings and may, according to more or less favourable conditions, increase or decrease the expected service life (Gaspar & de Brito, 2008). The general factor method formula is expressed by Equation (1):

$$ESL = RSL \times A \times B \times C \times D \times E \times F \times G \qquad (1)$$

where: ESL – represents the estimated service life; RSL – the reference service life; A – the material characteristics (quality, treatment and finishing); B – the design characteristics; C – the execution characteristics; D – the inner environment characteristics; E – the external environmental characteristics; F – the use conditions of the construction and G – the level of maintenance.

ISO 15 686 -8 (2008) refers that the durability factors should present realistic values, close to unity, proposing the adoption of the interval of 0.8 to 1.2, and more preferably, the durability factors should be in the interval of 0.9 to 1.1. However, it is an empirical method, which depends significantly on the data collected (Hovde, 2004). Moreover, it is criticized for the simplicity with which it addresses the real complexity of the degradation processes (Moser & Edvardsen, 2002; Re Cecconi, 2004), i.e. the result is the expected service life limit of the element under analysis, which does not provide information on the dispersion of the results (Bourke & Davies, 1999). Other limitations of this methodology are: i) the non-prioritization and the lack of hierarchy of the variables (all the factors have the same weight); ii) the considerable dependence on modifying factors and the difficulty in quantifying and organizing them hierarchically; iii) the high sensitivity and the assumption of a constant rate of degradation, not allowing understanding and characterizing the components' degradation over time (Rudbeck, 1999; Moser, 2004; Gaspar & de Brito, 2008; Silva et al., 2016). However, Gaspar and de Brito (2008) states that, despite being subjected to these and other criticisms, the factor method is the one with greater acceptance in the scientific community, being addressed in several studies with numerous variations and developments.

2. Degradation phenomena and loss of performance of ETICS systems

For the estimation of the service life of ETICS it is necessary to know their characteristics and the agents and mechanisms that influence the deterioration of their properties over time (Ximenes et al., 2015). A methodology for data gathering through simple visual inspections of façades exposed to various degradation agents was adopted. During fieldwork, the information concerning the characteristics of the systems, their degradation exposure and their deterioration condition were surveyed. The use of ETICS systems in Portugal is still relatively recent since the standard that establishes the thermal behaviour and performance requirements of buildings only started to be widely prescribed in the early 1990s (Ximenes et al., 2015), thus enforcing the necessity of adopting solutions that optimize the thermal behaviour of buildings. Therefore, it was very difficult to obtain claddings more than 20 years old.

The pathological manifestations detected in the claddings were aggregated in a classification system and the most frequent defects in ETICS were grouped in four distinct categories: i) staining/colour or texture changes – this group integrates biological growth, drainage signs, dirt deposits, humidity stains, efflorescence and oxidation stains, among others; ii) loss of integrity anomalies – this group includes cracking and deterioration of reinforcement corner profile caps and material gaps; iii) loss of adherence – this group includes peeling and blistering manifestations in façades; iv) joints anomalies – this group comprises cracking in joints and discernible joints between panels associated to dirt or humidity.

The first group of anomalies considered, related with staining/colour or texture changes, is very common in ETICS, affecting essentially their visual or surface degradation, and are not directly associated with the reduction of the functional performance of the systems (i.e. usually they do not affect the performance of the thermal insulation, the waterproofing characteristics, or the mechanical properties of the system) (Silva & Falorca, 2009), even though in some occasions these anomalies reveal the first sign of the presence of more serious anomalies that compromise the ETICS' performance. The other three groups of defects can be responsible for a loss of performance of ETICS, thus leading to a faster decay of the entire cladding system.

The information compiled during fieldwork was statistically treated, and the defects detected were weighted according to their severity, extent and impact, while defining probable causes for their occurrence. The discrete phenomena were excluded from this analysis since this methodology only considers degradation phenomena evolving over time, suitable to be modelled. The entire methodology described is based on the appraisal of the degradation state of 274 claddings in Portugal with ages up to 31 years. The age of the claddings is defined by the year of the application of the ETICS systems in the buildings.

2.1. Degradation model

After data collection, the service life prediction models can be defined. For each group of defects, five levels of degradation were defined through a visual and physical classification, ranging from 0 (no visible degradation) to 4 (generalized degradation), determined by the existing conditions analysed in situ (Figure 1). This degradation scale was set according to the defect type, severity, extension, intensity and effects of the defects detected. Therefore, the field data were converted into a numerical indicator, which allows quantifying the overall degradation of ETICS. This numerical index, called as degradation severity index (S_w) (Gaspar & de Brito, 2008, 2011) was calculated through the ratio between the weighted degraded extension of the cladding and the maximum level of possible degradation (Equation (2)), allowing a statistical comparison between the various claddings. This index allows graphically establishing the deterioration pattern of ETICS, through the definition of a global degradation curve (Figure 2) based on a simple regression analysis. This methodology was initially proposed by Shohet, Rosenfeld, Puterman, and Gilboa (1999), who defined different degradation patterns; among these patterns, the "S-shaped" curve seems the most relevant to illustrate the overall degradation of ETICS, representing a degradation phenomenon whose intensity changes over time, i.e. the degradation of ETICS occurs initially at a faster pace, revealing the occurrence

Condition 1
Barely perceptible changes
$1\% < S_w \leq 10\%$

Condition 2
Slight degradation
$10\% < S_w \leq 30\%$

Condition 3
Moderate degradation
$30\% < S_w \leq 50\%$

Condition 4
Generalized degradation
$S_w \geq 50\%$

Figure 1. Illustrative example of the degradation conditions of ETICS

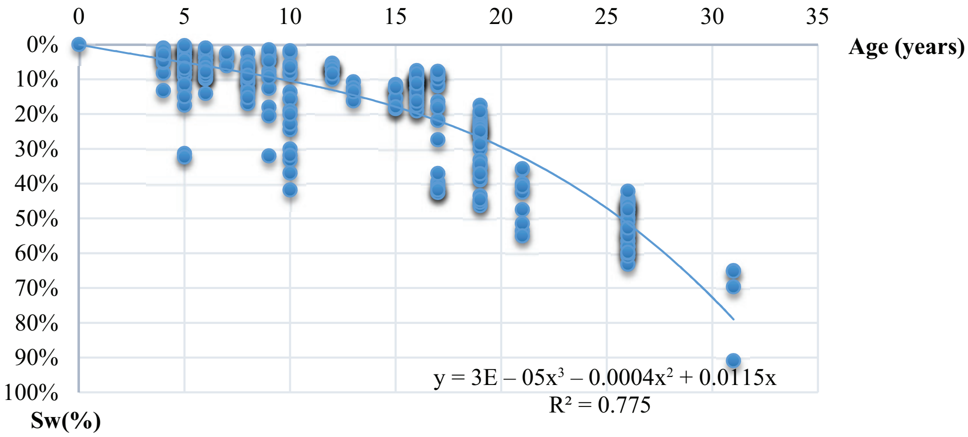

Figure 2. Degradation curve obtained from the 274 cases inspected in the fieldwork

of anomalies in earlier years, which apparently stabilize over time, accelerating again near the end of their service life (Silva, de Brito, & Gaspar, 2011, Silva et al., 2016). Therefore, to obtain a "S-shaped" pattern, which illustrates the physical phenomenon, a third-degree polynomial line was adjusted to the scatter of points belonging to the sample, using a methodology similar to the one proposed by Gaspar and de Brito (2008) and adapted by Ximenes et al. (2015). This curve represents the degradation of the sample over time.

$$S_w = \frac{E_w}{k} = \frac{\sum\left(A_n \times k_n\right)}{A \times k} \times 100 \,. \tag{2}$$

where: S_w – represents the degradation severity, expressed in percentage; E_w – the weighted degradation extension, expressed as a percentage; k – the multiplying factor corresponding to the highest degradation condition level of the cladded area A (in this case, $k = 4$); A_n – the cladding area affected by a defect n, in m^2; k_n – the multiplication factor for n anomalies, in terms of their degradation level, with the following possible values {0, 1, 2, 3, 4}, and A – the total façade area with ETICS, in m^2.

The determination coefficient (square of the Pearson product-moment correlation coefficient), associated with the degradation pattern, showed a relatively high value ($R^2 = 0.775$), which acceptably characterized the loss of performance of ETICS claddings (approximately 77.5% of the variability of the degradation is explained by the age of the claddings and the other 21.5% is due to other factors, not considered in this model). However, this curve also shows a significant scatter in the values, particularly evident when one considers that some of the cases with the same age are located in the same building. The observed dispersion can be justified, partially, by the high sensitivity of ETICS systems to the existing conditions of design, execution (as they rely heavily on proper design, execution and constructive detailing and on the application of adequate materials) and use. These factors were not considered in this analysis due to the difficulty in precisely evaluating this type of information only based on visual inspections. The curve configuration (a slightly "S" shaped pattern) also indicates that the claddings tend to show early changes that have a visual impact shortly after the end of the construction, whose actions evolves over time, increasing the degradation potential of the ETICS systems near the end of their service life (Shohet et al., 1999).

Consequently, the sample was evaluated according to different variables and their combined action, trying to identify the degradation factors that influence the durability of ETICS systems and their properties over time (these factors are the basis of the factor method's calculation). These factors concern mainly the claddings' characteristics and the environmental exposure conditions. In this regard, several regression curves were drawn and analysed, enabling the development of degradation models associated with each variable analysed. In this analysis, some variables did not allow drawing unequivocal conclusions due to their statistically insignificant results (when the sample was divided into several sub-factors, some categories presented a very small number of case studies). Some degradation curves also showed low determination coefficients, revealing a low statistical relevance. This result can be justified by the fact that the degradation agents act synergistically and, therefore, the degradation of ETICS must be analysed in more than one dimension. In this study, the degradation condition of ETICS was estimated based only on visual inspections; therefore, the case studies were analysed *in situ*, in some cases, many years after installation, and therefore some factors that may influence the degradation pattern were not considered due to the difficulty of accurately defining these parameters (e.g. the building envelope design, the preparation of the substrate, the mortar composition, the characteristics of the thermal insulation panel, the detailed evaluation of the execution conditions, among others). This study intends to analyse all the relevant factors to explain the degradation of ETICS, since their quantification is measurable during fieldwork, i.e. in this study only the variables and factors that can be visually measured are considered, e.g. colour, surface finishing, among others. In section 3, the durability factors considered were thoroughly discussed and analysed.

2.2. Extrapolation of the degradation curve for each point of the sample and calculation of the estimated service life for each case

There are different methodologies for the extrapolation of the average degradation curve to all the case studies in the sample. These methods are based on different approaches, namely: homothetic transformation; rotation method; translation method; ordinates' conversion factor method and the abscissas' conversion factor method (Gaspar & de Brito, 2008). In this research, the average degradation curve was extrapolated to the different cases using the method of ordinates' conversion factor method since it is the one that provides more reliable results and adopts uniform criteria to each point, being recognized for its simplicity of use (Emídio et al., 2014). The methodology applied is based on the identification of a factor *k*, which relates to the ordinates of two points. In this context, for two distinct points, *B* with coordinates (*x*, *y*) and *A* with coordinates (*x*, *y'*), the ratio between the ordinates is calculated and is subsequently applied to the function *f* with the aim of estimating a function *f*, correlated to the average degradation curve, which passes through each point of the sample (Equation (3)).

$$f' = \mathrm{k}\left(\mathrm{f}\right) \Leftrightarrow f' = k \cdot a \cdot x^3 + k \cdot b \cdot x^2 + k \cdot c \cdot x \tag{3}$$

where: *f* – represents the function of the average degradation curve of the type $\mathrm{a} \cdot x^3 + b \cdot x^2 + c \cdot x$; *k* – the conversion factor obtained by the ratio between the ordinates of points *A* (one point of the sample) and *B* (belonging to *f*); *f'* – represents the degradation curve from the family of the average degradation curve that passes through each point and *a*, *b*, *c* – constants of the 3rd degree polynomial average degradation curve.

In this study, two methodologies are applied in order to evaluate the service life of ETICS and in order to quantify the durability factors (Silva et al., 2016): i) the graphical method (GM), applying the extrapolation of the degradation curve for each point of the sample, estimating for each case study the age (x) in which the maximum allowable degradation level (y) is reached; i.e. the service life can be estimated for each case study through the graphical intersection between the curve for each case study and a horizontal line corresponding to the S_w considered as the maximum allowable degradation level; ii) the degradation curves (DCs), in which an average degradation curve is plotted for each one of the durability factors considered, estimating the average predicted service life for each characteristic through the intersection between the maximum degradation level and the average curve. In this study, it is considered that a cladding with a severity of degradation higher than 30% has reached the end of its service life.

Figure 3 shows the upper and lower limits of the degradation curve using the ordinates' conversion factor method. Based on this method, and through the intersection between the lower and higher limits with the maximum acceptable degradation level considered (S_w = 30%), the following results are obtained: i) for claddings with a high degradation condition, the upper service life limit is approximately 5 years (claddings represented below the average degradation curve); ii) for claddings in a better condition (above the average degradation curve), the maximum value for the service life is approximately 58 years (which is estimated through the intersection between the upper degradation curve and the maximum acceptable degradation level, corresponding in this case to a S_w of 30%).

The trend line, concerning the expected service life distribution of the claddings over time obtained through the graphical method, is shown in Figure 4 (the abscissas measure the variable age and the ordinates measure the variable expected service life).

This line represents the average expected service life of the sample (approximately 22 years). The value obtained is close to the one calculated through the average degradation curve (approximately 20 years). Notwithstanding the scatter shown in the graph, acceptable results were obtained.

In this study and adopting the same criteria as Emídio et al. (2014) and Galbusera, de Brito, and Silva (2015), all the cases that had a predicted service life higher than 40 years (twice the reference service life obtained through the

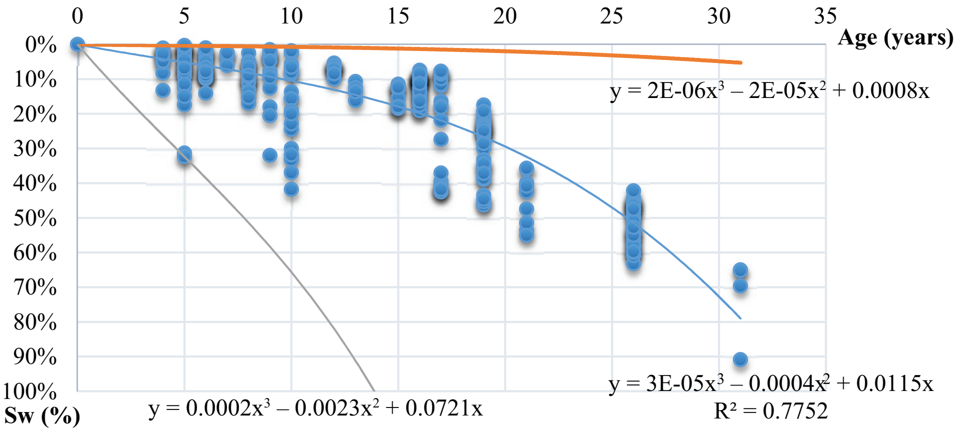

Figure 3. Upper and lower limits of the degradation curve using the ordinates' conversion factor method

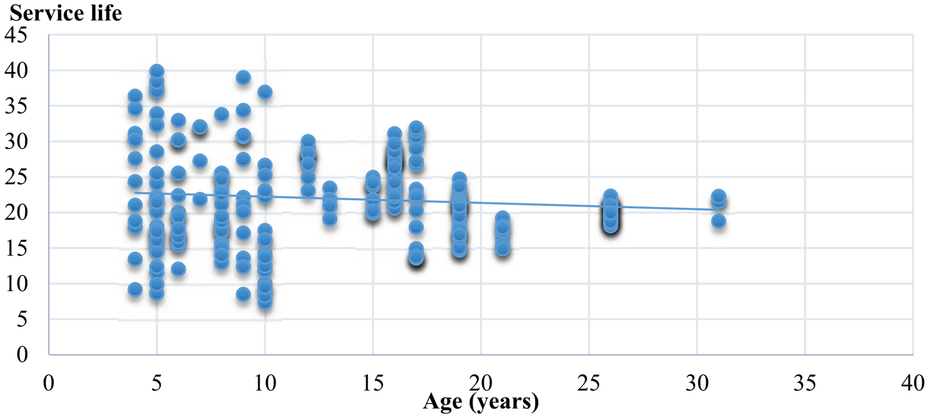

Figure 4. Service life distribution of the claddings over time

average degradation curve) or less than 5 years (25% of the reference service life) were excluded. The use of these criteria is found in the literature, which established a ranging of expected values of service life for ETICS systems. Kočí, Maděra, and Černý (2012) defines a minimum value for the ETICS' service life of 6 or 7 years, for claddings subjected to a very high level of degradation, very close to the one that has been adopted as the lower limit in this study (5 years). The upper service life limit (about 40 years) is supported by the study of Paczkowski (2013) that suggests the same value, and also Silva and Falorca (2009), who establish a maximum service life of 42 years. Based on these criteria, 10 case studies were excluded. Six of the case studies excluded present early ages (6 years), with lower levels of degradation (with a S_w lower than 2%). In fact, the model is not able to adequately predict the degradation evolution of these case studies, because the claddings are at an early stage of deterioration and their aging process is not appropriately modelled by this method.

3. Identification and weighting of the factors that influence the durability of ETICS systems

The sample was analysed according to different variables and their combined action, trying to understand how these factors influence the durability of ETICS systems over time. ISO 15 686 -2 (2012) proposes a quantification for the modifying factors, which may affect the loss of performance of the claddings. Thus, these parameters vary typically between 0.8 (for unfavourable situations) and 1.2 (for favourable situations). For current situations (similar to the reference conditions) or for variables difficult to quantify, weighting values equal to 1.0 are assigned. The adopted weighting coefficients are only indicative, being used in this study to calculate the reference service life. This quantification is proposed based on the service life determined through the degradation curves (D.C.) and the graphical method (G.M.) plotted for each variable, their physical meaning and their degradation patterns.

The durability factors proposed by ISO 15 686 -2 (2012) can be divided into: material characteristics (*A*), design characteristics (*B*), execution characteristics (*C*), inner environment characteristics (*D*), external environmental characteristics (*E*), use conditions (*F*) and level of maintenance (*G*). In the application of the factor method to the service life prediction of ETICS, not all these factors are analysed, some of them because it is not possible to obtain reliable information during fieldwork and others because they are not relevant for the description of the phenomena under analysis. In the following sections, each factor is described and its influence on the durability of the claddings is evaluated.

3.1. Factor *A* – material characteristics

The materials used in ETICS systems, their characteristics, functional requirements and the information about their quality and certification are not easy to characterize during fieldwork, which restricts the data gathering and the analysis of these parameters in the implementation of the factor method. For example, the characteristics of the different elements and layers of the ETICS cannot be analysed, since the case studies are analysed several years after application and there is no information regarding the type and composition of the mortar applied, as well the type of insulation system. Thus, factor *A* only considers the parameters for type and colour of the claddings, which have significant relevance and are easily identified during the visual inspections.

Table 1 shows the results for service life obtained for each sub-factor (type and colour) through the graphical method and the degradation curves, and their quantification (*k* value). The assigned *k* values took into account the physical meaning of the studied variables, the intrinsic characteristics of the materials and the relative average service life obtained through both methods. Thus, favourable situations were quantified with a higher or equal *k* value than current or unfavourable situations. In this context, for the type of cladding factor, the traditional system was quantified with a *k* value equal to 1.0 because it is associated with the type of ETICS system most commonly used (average situation), while other types of system (strengthened and ceramic) had a *k* value of 1.2, because they corresponded to more favourable situations (associated with higher strength capacity, revealing higher durability and service life). ETICS with ceramic claddings show more resistance when compared to strengthened claddings, with a higher expected service life calculated by the graphical method; however, it was not possible to determine the average estimated service life of these systems through the degradation curve, leading to some uncertainty, and, therefore, a value of *k* equal to 1.2 was also assigned.

Regarding the colour of the claddings, the same criteria were used. The results obtained by the average degradation curve seem more reliable since they reveal that the darker colours tend to present a lower estimated service life. Various authors (Daniotti & Paolini, 2008; Norvaišienė, Griciutė, Bliūdžius, & Ramanauskas, 2013; Fernandes et al., 2016b) refer that ETICS with dark colours tend to present a faster deterioration rate, especially in warm climates, when exposed for several hours to UV radiation, due to the higher thermal gradient effect. However, in some situations it is not possible to achieve conclusive results for a given characteristic of the ETICS, when analysed separately, since the degradation of ETICS is influenced by several factors and the presence of anomalies is generally caused by the combined action of various degradation agents, which may occur simultaneously, and whose synergy can change the normal pathology of the cladding systems after a long period of time (Amaro et al., 2013; Sulakatko, Lill, & Liisma, 2015). Therefore, in this case, this factor led to inconclusive results. For "other" colours, associated mainly with systems with ceramic tiles, *k* values equal to 1.2 were adopted, since these claddings present higher estimated service lives when compared

Table 1. Weighting values proposed by ISO 15 686-2 (2012)

Factors	Sub-factors		Number of cases	Determination coefficient (R^2)	Service life (average degradation curve)	Service life (graphical method)	*k* value
*A*1 – Type of system	*k*1	Traditional	257	0.77	20	22	1
	*k*2	Strengthened	10	0.74	31	22	1.2
	*k*3	Ceramic	7	0.49	–	28	1.2
*A*2 – Colour	*k*1	White	151	0.84	19	21	1
	*k*2	Light colours	64	0.67	21	21	1
	*k*3	Dark colours	51	0.54	19	25	1
	*k*4	Other	8	0.49	–	26	1.2
*B*1 – Type of finishing	*k*1	Rough	220	0.76	20	22	0.8
	*k*2	Smooth	47	0.86	20	22	1
	*k*3	Other	7	0.49	–	28	1.2
*B*2 – Protection level	*k*1	Peripheral profile	54	0.59	21	23	1.2
	*k*2	Wainscot	114	0.81	20	22	1
	*k*3	Other	106	0.67	20	21	0.8
*C*1 – Execution level	*k*1	Adequate	274	0.78	20	22	1
	*k*2	Inadequate	25	–	7	7	0.8
*E*1 – Orientation of the façade	*k*1	North / NE	51	0.42	21	21	0.8
	*k*2	South / SW	35	0.83	21	24	1.2
	*k*3	East / SE	57	0.69	20	22	1
	*k*4	West / NW	63	0.72	20	21	1
*E*2 – Distance from the sea	*k*1	< 1 km	–	–	–	–	0.8
	*k*2	Between 1 and 5 km	85	0.94	20	21	1
	*k*3	> 5 km	189	0.38	20	22	1.2
*E*3 – Humidity exposure	*k*1	High	112	0.82	19	21	1
	*k*2	Low	162	0.59	20	22	1.2
*E*4 – Exposure to wind/ rain action	*k*1	Severe	148	0.50	20	22	0.8
	*k*2	Moderate	82	0.85	20	21	1
	*k*3	Mild	44	0.86	17	21	1.2
*E*5 – Pollution exposure	*k*1	High	93	0.29	21	22	1
	*k*2	Low	181	0.85	20	22	1.2
*G*1 – Ease of inspection	*k*1	Yes	90	0.74	20	22	1.2
	*k*2	No	184	0.80	21	22	1

with the other colours (white, light colours and dark colours – all assigned with a *k* value of 1.0), whose occurrences are regarded as current in the sample analysed.

3.2. Factor *B* – design characteristics

Errors or omissions resulting from the design phase may be responsible for the premature loss of performance of the claddings, leading to anomalies that could be easily prevented or avoided with appropriate design features. The factor related to the design characteristics is very difficult to evaluate because it depends on various aspects that are not easily identified by simple visual inspections of several years' old elements, such as incorrect design of elements and fastening systems, poor constructive detail, among others. Nonetheless, at this stage, the design characteristics analysed are the type of finishing and the protection level, because these characteristics can be easily evaluated in a field survey. Table 2 presents the sub-factors considered and the corresponding service lives calculated using the degradation curves and the graphical method.

For the type of finishing, a value of *k* of 1.2 has been assigned to "other" types of finishing (ceramic finishing), corresponding to the most favourable condition, with higher estimated service lives. Claddings with rough finishing are regarded as the least favourable (*k* value of 0.8), because their texture promote the accumulation of dirt and microorganisms responsible for a number of serious defects (Ximenes et al., 2015). Smooth finishing appears as an intermediate situation between these two types of textures and, consequently, a neutral value is attributed (*k* value equal to 1.0).

Table 2. Quantification of the durability sub-factors for the scenarios adopted

Factors	Sub-factors		Service life (average degradation curve)	Service life (graphical method)	Scenario 1	Scenario 2	Scenario 3	Scenario 4
*A*1 – Type of system	*k*1	Traditional	20	22	1.000	1.000	1.000	1.000
	*k*2	Strengthened	31	22	1.000	1.200	1.100	1.100
	*k*3	Ceramic	–	28	1.000	1.200	1.100	1.250
*A*2 – Colour	*k*1	White	19	21	1.000	1.000	1.000	1.100
	*k*2	Light colours	21	21	1.000	1.000	1.000	1.000
	*k*3	Dark colours	19	25	1.000	1.000	1.000	1.400
	*k*4	Other	–	26	1.000	1.200	1.100	1.400
*B*1 – Type of finishing	*k*1	Rough	20	22	1.000	0.800	0.900	0.900
	*k*2	Smooth	20	22	1.000	1.000	1.000	1.000
	*k*3	Other	–	28	1.000	1.200	1.100	1.100
*B*2 – Protection level	*k*1	Peripheral profile	21	23	1.000	1.200	1.100	1.115
	*k*2	Wainscot	20	22	1.000	1.000	1.000	1.100
	*k*3	Other	20	21	1.000	0.800	0.900	0.775
*C*1 – Execution level	*k*1	Adequate	20	22	1.000	1.000	1.000	1.000
	*k*2	Inadequate	7	7	1.000	0.800	0.900	0.800
*E*1 – Orientation of the façade	*k*1	North	21	21	1.000	0.800	0.900	0.800
	*k*2	South	21	24	1.000	1.200	1.100	1.000
	*k*3	East	20	22	1.000	1.000	1.000	1.000
	*k*4	West	20	21	1.000	1.000	1.000	1.000
*E*2 – Distance from the sea	*k*1	< 1 km	–	–	1.000	0.800	0.900	0.800
	*k*2	Between 1 and 5 km	20	21	1.000	1.000	1.000	1.000
	*k*3	> 5 km	20	22	1.000	1.200	1.100	1.100
*E*3 – Humidity exposure	*k*1	High	19	21	1.000	1.000	1.000	1.000
	*k*2	Low	20	22	1.000	1.200	1.100	1.150
*E*4 – Exposure to wind/rain action	*k*1	Severe	20	22	1.000	0.800	0.900	0.800
	*k*2	Moderate	20	21	1.000	1.000	1.000	0.900
	*k*3	Mild	17	21	1.000	1.200	1.100	0.950
*E*5 – Pollution exposure	*k*1	High	21	22	1.000	1.000	1.000	0.950
	*k*2	Low	20	22	1.000	1.200	1.100	1.100
*G*1 – Ease of inspection	*k*1	Yes	20	22	1.000	1.200	1.100	1.100
	*k*2	No	21	22	1.000	1.000	1.000	1.000

Regarding the protection level, as expected, the façades with peripheral profiles show a better performance, with higher estimated service lives, than the other types analysed. Both methods indicate that ETICS with peripheral profiles are more durable, thus revealing that this factor positively influence the claddings' performance. This idea is reinforced by Ximenes et al. (2015), who refers that systems with peripheral profiles are better protected from accidental and intentional actions. Conversely, the claddings with "other" type of protection (claddings less protected in accessible areas) have a lower service life calculated through the graphical method, justified by the lower protection offered by these solutions to ETICS systems, especially from accidental actions (*k* value of 0.8). Although the existence of wainscot can help improve the protective function of the façades, it does not provide the same conditions as the existence of peripheral profile, being therefore quantified with a *k* value equal to 1.0.

3.3. Factor *C* – characteristics of execution

The execution level clearly distinguishes the greater durability of claddings subjected to appropriate design and application procedures when compared to claddings without such care. The most common mistakes in the implementation phase are related with: i) inadequate planning of the execution works; ii) lack of specific qualifications of labour; iii) inadequate preparation of the support; iv) misuse of the system components; v) absence of quality control; and vi) insufficient treatment of singular points.

These factors are not easily recognized because of the impossibility of identifying all existing conditions at the time of the preparation and application of the ETICS systems. Thereby, during fieldwork, all the claddings that had obvious execution errors were identified. There are different execution errors that can be identified during the fieldwork, namely: i) the insufficiency or absence of reinforcement in the corners of the openings of the walls (which is a very common error and is easily recognized during fieldwork); the absence of the reinforcement in these sites associated with the concentration of stresses usually leads to a strong tendency for the appearance and evolution of cracking defects; ii) the presence of detachment in ETICS is, in some situations, associated to execution errors, as the use of inadequate materials (application of non-homologated products or the incorrect handling and conservation of the products applied), incompatibility between the different layers of the system, poor application of products or inadequate application of the constituents of the system (e.g. insufficient thickness of the different layers of the system), inadequate preparation of the substrate (lack of preparation and cleaning of the support) and inadequate treatment of singular points, the application of the system under adverse conditions of temperature and humidity; iii) the presence of discontinuities, in some occasions, due to errors during the application of the thermal insulation panels or the irregularities of the layers of the ETICS system or their finishing material (this anomaly can also be caused by accidental events, as the impact of objects in the system).

Figure 5 shows two examples of façades: one with a good execution (left) and the other with obvious execution mistakes (right). In this last example, the execution errors were easily identifiable due to the loss of adherence and the detachment of the ETICS systems along the entire length of the lower portion of the façade, which were aggravated by the lack of protection in accessible areas. Although claddings with an inferior execution level are unrepresentative (only 25 façades, with only two different ages, do not allowing obtaining unequivocal conclusions), there is a fairly significant difference in their service life expectancy compared with the claddings with an adequate execution level (Table 1). An inadequate or deficient execution level strongly affects the durability of ETICS, clearly reducing their expected service life. In the sample analysed, ETICS with an inadequate execution level present an average estimated service life of 7 years, which is in accordance with the study performed by Kočí et al. (2012), which refers that the building envelope always behaves as a system, and thus the service life of the entire system can be conditioned by the durability of each component, which in extreme conditions can limit the service life of ETCS to 6 to 7 years.

In this study, the claddings exhibiting severe execution errors were removed from the sample (since these situations do not translate the normal evolution of the degradation phenomena over time) and, therefore, these cases were not taken into account in the definition of the factors.

3.4. Factor *D* – inner environment conditions

This factor is not considered in this study because the conditions of the inner environment do not affect the durability of the external claddings.

3.5. Factor *E* – external environmental conditions

The external environmental characteristics are extremely relevant for the loss of performance of ETICS systems. The action of environmental factors on the claddings is also responsible for their degradation process and is therefore decisive for the modelling using the factor method. In this factor, five sub-factors were analysed (Table 1): i) façades orientation; ii) distance from the sea; iii) exposure to damp; iv) wind-rain action; and v) exposure to pollution sources.

Figure 5. Comparison between two façades with ETICS:
one with good execution (left) and the other with execution mistakes (right)

The results obtained for the façades orientation (North, South, East and West) are plausible and consistent with reality; façades facing North and West feature the lowest expected service life when the graphical method is used, while the façades facing South have slower decay trends, showing the best behaviour. These results are reliable because façades facing North are cooler and more susceptible to moisture and biological growth (Kuenzel & Sedlbauer, 2001; Barreira, de Freitas, & Delgado, 2013), and façades facing West are more exposed to solar radiation, facing in some cases, more abrupt temperature gradients (Barreira & Freitas, 2013; Gómez-Heras, Smith, & Fort, 2008), which compromises the performance of ETICS over time. Therefore, the North/NE and South/SW orientations were quantified with a *k* value equal to 0.8 (unfavourable) and 1.2 (favourable), respectively. Façades facing East/SE and West/NW are considered as intermediate situations with a large preponderance in the sample, presenting in both cases a k value equal to 1.0.

Regarding distance from the sea, the proposed quantification is intuitively understood. ETICS with unfavourable exposure are assigned with a *k* value equal to 0.8. For claddings subjected to more favourable conditions, a value of 1.2 is proposed. In intermediate situations or when there is not enough representation in the overall sample (a neutral weighting value of 1.0 is assumed. Concerning distance from the sea, due to the scarceness of cases located less than 1 km from the sea, it is not possible to estimate the service life of these claddings; claddings located between 1 and 5 km from coastal areas show a faster degradation pattern than cases located more than 5 km from the sea, when the graphical method is used. These results comply with empirical expectations, because buildings closer to the sea are subjected to stronger winds that carry moisture, dirt and soluble salts (Ximenes et al., 2015).

The data obtained with the degradation curves method for the combined rain-wind action contradicts empirical expectations, since ETICS with mild exposure present higher degradation indexes than ETICS with severe and moderate exposure to wind-rain action. Through the graphical method, the results obtained were similar, with the claddings subjected to a severe action having a longer service life than the claddings with more favourable exposure conditions. The fact that there are few claddings in the sample that are subjected to a mild exposure (44 claddings in which 40 cases have ages equal to or less than 5 years and 4 cases are 31 years old) and no claddings older than 22 years subjected to a severe action may explains these results.

Concerning exposure to damp and distance from pollution sources, values equal to 1.2 were adopted for the most favourable situations ("low" exposure in both variables). For the sub-factor relating to exposure to damp, the service life values obtained for "high" and "low" exposure are very similar: the claddings with "high" exposure to damp (buildings situated near rivers or the sea) deteriorate faster and have a slightly lower service life than claddings with "low" exposure (obtained through the two methods). These findings are coherent with the results obtained by Ximenes et al. (2015), but must be cautiously analysed, given the low statistical significance of the models due mainly to the insufficient number of claddings with "low" exposure to damp with ages equal or higher than 19 years. Therefore, since it was not possible to obtain clear conclusions, a neutral indicator was chosen to quantify the "high" exposure to damp (*k* equal to 1.0). Similarly, the outcomes regarding the pollution exposure are rather inconsistent, needing further investigation. The claddings with a lower exposure to pollution sources present a similar estimated service life to the ones situated near intensive traffic routes (with a higher exposure to these agents), although the results are not statistically significant due to the lack of "high" exposure cases in the sample with more than 17 years, which skew the results. Thus, a weighting value of 1.0 was adopted for the case studies with "high" exposure to pollution sources.

3.6. Factor *F* – use conditions

Frequent errors or inadequacies of use are mainly due to impacts, vandalism (especially in accessible areas), improper repairs or absence of periodic maintenance. However, the degradation caused by these errors cannot be modelled from a service life prevision perspective according to the methodology used (as degradation does not evolve in a predictable manner over time) and therefore these factors is excluded from the analysis.

3.7. Factor *G* – maintenance conditions

In terms of the maintenance level, only the factor "ease of inspection" was analysed. Clear evidence of regular maintenance was not observed in any of the case studies, thus this sub-factor was not considered in the analysis. Although ease of inspection is not the most relevant factor for the durability and service life prediction of ETICS, the results obtained reveal that façades that facilitate the visual survey of the degradation state present a slightly faster deterioration than the claddings not easily inspected (Table 1). This result can be justified by two main reasons: i) the anomalies are easily identified in ETICS with easy inspection conditions, and conversely it is more difficult to evaluate the degradation condition of ETICS in not accessible areas; ii) ETICS not easily inspected are associated with higher buildings, therefore more subjected to the environmental degradation agents. However, the service life values for the two situations are quite close regardless of the method used. Thus, it would be expected that the two variables would have the same k value. Nevertheless, it is considered that a situation where the inspection is easy to perform is more favourable because the lower height of the buildings (up to three storeys high) and the greater accessibility of the façades enable a clearer and more precise reading of the degradation of the claddings, and therefore this sub-factor was quantified with a *k* value equal to 1.2. In façades not easily inspected (with limited inspection conditions), any errors of interpretation of the anomalies may influence the calculation of the estimated service life for these cases. As there is no clear conclusion on this variable, it was assigned a coefficient of 1.0.

4. Reference service life

The concept of reference service life, used to characterize the expected durability of the claddings, is not simple to define or evaluate. According to Rudbeck (1999), citing BSI 7543 standard (1992), this value may be determined by scientific research based on specific laboratory test results or statistics; by previous experience with similar construction elements or by the analysis of the degradation level of the elements, evaluating their durability limit. Given the vagueness that some of those methods present, the author emphasizes the need to adopt more than one of these methods, with subsequent comparison of the results. ISO 15 686 -2 (2012) also describes a method to determine the reference service life, based mainly on accelerated ageing tests and their comparison with the technical information provided by manufacturers or experts and, possibly, with information obtained from visual inspections. In this study, this value is analytically determined, using data obtained from a statistically significant number of ETICS claddings inspected *in situ*.

The global degradation curve intended to translate the evolution of the behaviour of ETICS over time, through the graphical representation of the loss of performance of the overall sample analysed. Simultaneously, the method allows determining the sample reference service life based on the setting of a maximum acceptable degradation level or minimum acceptable performance level. In this context, the same criterion as Gaspar and de Brito (2008) and Ximenes et al. (2015) was applied, which defined the degradation level 3 (moderate degradation – $S_w = 30\%$) as the service life limit for ETICS systems. Thereby, claddings with a degradation level of 3 or higher are assumed to have reached the end of their service life and are not appropriate to perform their expected functions, requiring some intervention (repair and/or substitution of elements) in order to re-establish their original characteristics and the capacity to fulfil all the performance requirements. It is important to note that this value varies according to what is considered the acceptable maximum degradation limit and also varies according to the social context of its evaluation, the characteristics of the materials and the performance expectations (Chai, de Brito, Gaspar & Silva, 2014; Silva et al., 2015).

Moser (1999, 2004) reveals that the end of service life is influenced by functionality, appearance and safety criteria, and this limit is reached when one of these principles is no longer satisfied. The conservation of the integrity of the buildings in a standard security level is considered as an essential criterion, thus presenting a higher demand level than the other requirements; although in most cases, the end of service life is only imposed by aesthetic appearance criteria (Moser, 2004; Emídio et al., 2014), which usually reaches its admissible minimum performance level sooner.

The reference service life could be determined through the intersection of the average degradation curve with the horizontal line that represents the maximum acceptable degradation level ($S_w = 30\%$). In a more rigorous way, the reference service life value can also be obtained by solving the equation of the regression curve in order to x for y equal to 0.30, yielding a value of approximately 20 years. Considering the significant influence of this value in the modelling through the factor method, two other methods were applied in order to minimize the uncertainty and the subjectivity associated to this value. The first method is the method of the average exposure conditions for the best case and the second is the method of the average conditions for the whole sample, defined and developed by Gaspar and de Brito (2008) and also adopted by Emídio et al. (2014) and Galbusera et al. (2015).

The first model adopts the weighting values for the sub-factors of the factor method proposed by ISO 15 686-2 (2012) – 1.2, 1.0 and 0.8 – and uses the predicted service life values calculated through the method of ordinates' conversion factor method. The objective of this method is to find claddings exposed to an intermediate situation (all variables take values equal to 1.0 – average situation). However, in the sample analysed, none of the case studies show these characteristics and, therefore, the closest values to this situation (with a higher number of variables equal to 1.0) were identified. Subsequently, the occurrences of the values 0.8 (x) and 1.2 (y) for the sub-factors were counted and the predicted service life value was calculated by considering the average of the values of all the cases with the mentioned characteristics. The formula used to calculate the reference service life of the claddings is expressed by Equation (4) (Emídio et al., 2014). The reference service life calculated using this method was 21.4 years.

$$\text{Reference service life} = \frac{\text{Predicted service life}}{\left(0.8^{x} \times 1.2^{y}\right)} \tag{4}$$

Once again, in the method of the average conditions for the whole sample, the reference values provided by the ISO 15 686 -2 (2012) were used. In this methodology, the ratio between the predicted service life and the reference service life calculated by the previous method was evaluated. In principle, only the ratios with deviations from the total average below 3% were considered. Taking only these cases into account, the average of the reference service life was calculated, leading to a value equal to 20.7 years.

Therefore, three values of the reference service life were estimated through the three methods used: i) 20.2 years is obtained based on the average degradation curve; ii) 21.4 years is achieved with the method of the average exposure conditions for the best case; and iii) 20.7 years is obtained by the method of the average conditions for the whole sample. The reference service life for ETICS was set at 21 years, corresponding to the average of the three values stated above.

As mentioned by Silva and Falorca (2009), to predict the service life of ETICS located in Portugal is still difficult, since this cladding system is being applied only for 15 years, in a limited number of buildings (the case studies to be modelled are rare). The authors also refer that ETICS are a multilayer cladding, which is an additional challenge, when the intention is to define an overall degradation pattern for a cladding solution. Therefore, currently, there are different standards and studies that propose different values for the reference service life of ETICS. It is important to notice that the values proposed in this study correspond to a reference service for ETICS not subjected to any maintenance action during their service life, for a maximum level of degradation of 30% (Figure 1 shows an illustrative example of the degradation condition of ETICS with a severity of degradation of 30%). Naturally, if a stricter demanding level were applied, the reference service life of ETICS would decrease and, on the contrary, if the maximum acceptable degradation level increased, the reference service life would also increase. Nevertheless, the results achieved by the three models were coherent, revealing a good fit to reality, being coherent with the values defined by various publications such as: CSTB (1981), which refers a service life equal or higher than 30 years; ETAG 004 (2000), which suggests a service life higher than 25 years for ETICS claddings subjected to regular maintenance actions; Silva and Falorca (2009), who suggested a predicted service life value between 24 and 28 years for ETICS systems, without maintenance; Zavrl, Selih, and Zarnic (2007) refer that, even though the Slovenian regulation about maintenance of residential buildings established the service life of ETICS in 25 years, these systems often suffer from mould growth on north oriented facades at very earlier stages of their service life; Liisma, Raado, Lumi, Lill, and Sulakatko (2014) refer that the actual service life of ETICS tends to remain below the 25 years established by ETAG 004 (2004); a study performed by Sulakatko et al. (2015) reveal that, based on 10 years of experience in rehabilitation and renovation of ETICS in Estonia, the first signs of deterioration might occur less than one year after installation; Liisma et al. (2014), comparing the Portuguese and the Estonian reality, refer that under Nordic climate conditions, in the case of Estonia, the first signs of pathological situations occurs within 1–6 years, instead of 10 to 20 years as in Portugal; Künzel, H., Künzel, H. M., and Sedlbauer (2006) refer that 20 years is the mean frequency of refurbishment in ETICS (which is the same concept applied in this study, i.e. the end of service life corresponds to the instant after which the cladding no longer fulfil the performance requirements – based on the demanding level applied in this study –, thus requiring a maintenance or rehabilitation action).The latter studies are the ones that present the closest values to the one calculated for the sample analysed in this study because they refer also to ETICS claddings without any maintenance interventions.

5. Application of the factor method to the estimation of the durability of etics

5.1. Calculation formula

The factor method, initially proposed by the Architectural Institute of Japan (1993) and developed by ISO 15 686-2 (2012), establishes a mathematical equation, applied to all the claddings in a sample, intending to estimate the service life of a specific construction element exposed to particular conditions. Equation (5) shows the formula that allows estimating the service life of ETICS based on the durability factors identified in this study as influential in the claddings' degradation process.

$$ESL = RSL \times A1 \times A2 \times B1 \times B2 \times C1 \times E1 \times E2 \times E3 \times E4 \times E5 \times G1 \tag{5}$$

where: *ESL* – represents the estimated service life; *RSL* – the reference service life (equal to 21 years, according to the values obtained in this study); *A*1 – the type of cladding system; *A*2 – the colour; *B*1 – the type of finishing; *B*2 – the protection level; *C*1 – the execution level; *E*1 – the façades orientation; *E*2 – the distance from the sea; *E*3 – the exposure to damp; *E*4 – the wind/rain action; *E*5 – the exposure to pollution sources and *G*1 – the ease of inspection.

5.2. Quantification of the factor method's sub-factors

Table 1 presents the estimated service life of ETICS for the different characteristics analysed, according to the two methods proposed: the average degradation curve; and the graphical method. These results portray the degradation patterns observed during fieldwork, which allow evaluating which categories in each sub-factor analysed correspond to the unfavourable or favourable situations (i.e. evaluating the effect of each category to increase or decrease the estimated service life of the ETICS in comparison with the overall degradation curve for the whole sample). Moreover, in section 3, the influence of the different sub-factors for the durability of ETICS systems during their service life was discussed in detail. In the following scenarios, the assigned *k* values consider the physical meaning of the variables (ensuring their plausibility and coherence with reality), assigning to the favourable situations a higher or equal *k* value than current or unfavourable situations (which should present the lowest *k* value). Therefore, for ETICS systems, the following patterns can be identified:

- Regarding sub-factor *A*1, related with the type of cladding system, the ETICS system with ceramic cladding is considered as the "favourable" situation, since this type of cladding presents good impact resistance, thus improving the behaviour under fire (Malanho & Veiga, 2011); the traditional type is considered as the current situation (since it is the most common situation), and the strengthened ETICS represents the intermediate situation;
- Concerning sub-factor *A*2 (colour of ETICS), light coloured systems and with smooth finishing present higher reflectance to UV radiation, thus minimizing the occurrence of anomalies due mainly to internal stresses and dimensional variations of thermal origin (Teo, Chew, & Harikrishna, 2005). However, the results obtained in the fieldwork do not allow

obtaining unequivocal conclusions, maybe because, even though dark colours should present higher degradation indexes, these colours tend to mask the pathological situation of the facades analysed based only on visual inspections. In the following scenarios, dark colours and "others", associated with ceramic claddings, correspond to the "favourable" situation (more durable, with higher estimated service lives), and light colours are assigned with a *k* value equal to 1, corresponding to the current situation (with the lowest *k* value);

- In terms of the type of finishing (*B*1), the "other" type of finishing (ceramic finishing) correspond to the "favourable" situation, for the reasons previously discussed. ETICS with rough finishing correspond to the "unfavourable" situation, since their texture promotes the accumulation of dirt and microorganisms, which accelerates the degradation of ETICS, reducing their service life (Ximenes et al., 2015);
- In factor *B*2, related with the protection level, it is considered that ETICS with peripheral profiles correspond to the "favourable" situation (with higher estimated service lives); on the opposite, claddings with "other" type of protection correspond to the "unfavourable" situation, since this solution is more susceptible to accidental and intentional actions;
- Regarding the execution level (C), inadequate conditions correspond to the "unfavourable" situation, and adequate conditions to the "current" situation, with a *k* value equal to 1;
- Concerning façades orientation, those facing north are considered the "unfavourable" situation, as discussed in section 3.5; in some scenarios, façades facing south are considered the most favourable condition;
- For the distance from the sea (*E*2), ETICS at less than 1 km from the sea correspond to the "unfavourable" situation; ETCIS between 1 and 5 km from the sea correspond to the "current" situation and ETICS at more than 5 km from the sea correspond to the "favourable" situation. These criteria are also applied for the quantification of the remaining factors related with the environmental exposure conditions, i.e. ETICS subjected to "unfavourable" conditions (high exposure to damp, severe exposure to wind-rain action, high exposure to pollution sources) are assigned with a lower *k* value, and the ETICS with "favourable" conditions are assigned with the higher *k* value;
- Concerning the ease of inspection (*G*1), ETICS easily inspected are assigned with a higher *k* value, corresponding to the "favourable" situation.

Based on these assumptions, thoroughly discussed in section 3, four scenarios were analysed, performing several iterations, to optimize the results and improve the reliability of the weighting coefficients. The criteria that led to the quantification of the sub-factors in each scenario are listed below.

Scenario 1

In the first scenario, a weighting value of 1.0 is attributed to all the sub-factors, analysing the neutral behaviour of the model, evaluating the usefulness of the factor method for the description of the degradation of the ETICS. If this scenario leads to the best overall results, then the factor method is unable to predict the estimated service life of ETICS, revealing that the characteristics of the system do not influence their degradation.

Scenario 2

In this model, the values adopted are the ones prescribed in ISO 15 686 -2 (2012): 0.80 for unfavourable situations; 1.2 for favourable situations; and 1.0 for current situations or for variables with a difficult evaluation (when the degradation curves or the graphical method do not allow obtaining unequivocal conclusions regarding the influence of these characteristics for the degradation of ETICS). For the quantification of the durability factors, the criteria previously discussed were applied, considering the estimated service life obtained by the average degradation curve and for the graphical method, always ensuring the coherence of the assigned values with the physical reality.

Scenario 3

In scenario 3, the criteria adopted are similar to the principles used in scenario 2. The values attributed to the *k* subfactors are 0.90, 1.0 and 1.1 (as suggested in ISO 15 686-2). The range of values adopted in this scenario is tighter than the one proposed in scenario 2 so as to analyse the model's sensibility to small variations and the contribution of these variations to the sub-factors quantification.

Scenario 4

This model is based on the results of the previous scenarios and considers the physical meaning and the influence of each variable in the degradation of ETICS. In this scenario, the *k* values are obtained by a successive manual iterative process to minimize the deviation between the values estimated by the factor method and the values observed during fieldwork. The quantification of the values in this scenario are analysed to the third decimal digit, since small variations in the quantification of the durability factors strongly influenced the estimated service life obtained by the factor method.

Criteria adopted for the discussion of the different scenarios analysed

These scenarios were evaluated through the comparison between the results obtained by the factor method and those obtained by the graphical method (which portrays the physical reality observed during the fieldwork) (Gaspar & Brito, 2008).The evaluation and the interpretation of the results obtained in this study were based on statistical indicators (cumulative frequency, standard deviation, average, maximum and minimum values) adopted in previous studies (Emídio et al., 2014; Galbusera et al., 2015). Therefore, some principles were adopted, considering the results estimated by the application of two methods (FM indicates the values obtained through the factor method and GM refers to the values achieved through the graphical method) and with the objective of achieving physically credible results. These principles are as follows:

- The maximum value for the average of the ratio FM/GM should be 1.05, which means that the average of the FM/GM ratios should not differ from 1 by more than 5%;
- The standard deviation average relative to 1.0 should be minimized, i.e. in a perfect model, the values achieved by the FM should be equal to the values achieved by the GM, and therefore, higher deviations of the FM/GM ratio reveal a model that is unable to accurately predict the service life of ETICS;
- The amplitude of expected service life results obtained through the factor method should be lower than the range of values obtained through the graphical method ($FM_{max} - FM_{min} \leq GM_{max} - GM_{min}$);
- The results achieved through the factor method should be coherent with the expected reality. Therefore, the maximum estimated service life was set as twice the reference service life (42 years) and the minimum estimated service life is equal to 15% of the reference service life (3.15 years);
- The cumulative frequency of FM/GM equal to or higher than 0.85 should correspond at least to 50% of the sample, i.e. the method should lead to conservative estimations;
- The cumulative frequency of FM/GM equal to or higher than 1.50 should correspond at most to 10% of the sample, which means that the failed estimations (i.e. when the values predicted by the FM exceeds by 50% the values observed during the fieldwork) should be limited to 10%, thus ensuring the accuracy of the model;
- The main objective of the various iterations is to maximize the number of cases contained in the interval of 0.85 and 1.15 for the FM/GM relation.

6. Discussion of the results

Table 2 presents the quantification of the durability subfactors for the scenarios adopted, while Table 3 illustrates the statistical indicators obtained through the analysis of the considered scenarios, after the factor method application. The results that do not fulfil the expressed criteria are in bold (Table 3).

The best weighting coefficients combination was reached in scenario 4, since they are estimated based on the optimization of the values that minimize the deviation between the predicted and the observed values. This scenario produced the best results and, therefore, validated the applicability of the methodology.

Statistically, scenario 2 led to the worst results, not fulfilling many of the defined criteria, particularly presenting the worse ratio FM/GM (1.16 >1.05). Even though scenario 3 shows slightly better results than the previous one, this scenario does not fulfil the requirements, presenting the lower cumulative frequency of FM/GM included in the range 0.85 and 1.15 (38.8%).

Scenario 1 leads to satisfactory and significant results, fulfilling all the defined criteria. However, this scenario was only considered with the purpose of studying the neutral behaviour of the model and, therefore, does not have physical meaning. These results can explain the slightly better results that scenario 3 presents when compared to scenario 2: the narrower range of values (0.9, 1.0 and 1.1) is closest to the neutral model studied in scenario 1 than the reference values provided by ISO 15 686 -2 (2012) (0.8, 1.0 and 1.2).

The adjustment and the manual optimization process of the values in scenario 4 have led to the best results and the fulfilment of all the requirements, giving due emphasis to the highest percentage of elements featuring a ratio FM/GM between 0.85 and 1.15 (52.9%) and the lowest standard deviation average in relation to 1.0. The estimated service life value obtained by this scenario through the factor method (approximately 21 years) is similar to the one calculated through the average degradation curve (around 20 years), reinforcing the notion that the values determined in this model are adequate to study this specific sample.

Table 3. Statistical indicators of the results obtained for each scenario

Scenario		1	2	3	4
FM/GM average < 1.05		1.04	**1.16**	**1.11**	1.03
Standard deviation		0.36	0.52	0.40	0.34
Standard deviation average in relation to 1.0		0.25	0.33	0.27	0.24
Amplitude of results	Factor method (years)	20.7	**47.3**	**33.8**	28.0
	Graphical method (years)	32.5	32.5	32.5	32.5
Extremes values obtained in the factor method	Maximum = 42 years	41.5	**61.9**	**51.9**	40.0
	Minimum = 3.15 years	20.7	14.7	18.1	12.0
FM/GM ≥ 0.85 (≥50%)		70.0%	73.8%	74.1%	74.1%
FM/GM ≥ 1.50 (< 10%)		9.1%	**15.2%**	**12.6%**	8.4%
0.85 ≤FM/GM ≤ 1.15		42.2%	38.8%	39.2%	52.9%

The results can be considered reasonable, considering the variability of the conditions influencing the degradation of ETICS systems, revealing that the optimized weighting coefficients should be close to the ones achieved through a neutral model (scenario 1 – standard conditions). Summarily, the k values that optimize the results should be close to 1.0, without great variations, in order to validate the credibility of the values and, simultaneously, minimize the deviations (Table 3). The fact that many of the coefficients adopted in the various scenarios are equal to 1.0 confirms these considerations. Such quantification suggests that many of the variables in this study did not significantly influence the durability of the ETICS systems.

6.1. Practical application of the model to real case studies

Based on the analysis performed in this study, scenario 4 is proposed to quantify the durability factors related with the ETICS systems. Using these sub-factors, it is possible to predict the estimated service life of any case study, based on its characteristics. To illustrate the proposed methodology, three case studies are analysed (presented in Figure 6).

Case study (A), has 17 years and has the following characteristics: *A*1 – traditional; *A*2 – light colours (pink); *B*1 – rough finishing; *B*2 – wainscot in stone; *C*1 – adequate conditions; *E*1 – North; *E*2 – more than 5 km from the sea; *E*3 – high exposure to damp; *E*4 – moderate exposure to wind-rain action; *E*5 – high exposure to pollutants; *G*1 – easy to inspect. Case study (B), has 6 years and shows the following characteristics: *A*1 – traditional; *A*2 – dark colours (grey); *B*1 – rough finishing; *B*2 – wainscot; *C*1 – adequate conditions; *E*1 – West; *E*2 – between 1 and 5 km from the sea; *E*3 – high exposure to damp; *E*4 – moderate exposure to wind-rain action; *E*5 – low exposure to pollutants; *G*1 – not easy to inspect. Finally, case study (C) has 5 years and presents the following characteristics: *A*1 – traditional; *A*2 – white; *B*1 – smooth finishing; *B*2 – other type of protection (elevated cladding in a building with a socle with other type of cladding); *C*1 – adequate conditions; *E*1 – Northeast; *E*2 – more than 5 km from the sea; *E*3 – low exposure to damp; *E*4 – mild exposure to wind-rain action; *E*5 – high exposure to pollutants; *G* – easy to inspect. Equations (6) to (8) show the calculation of the estimated service life of the three case studies analysed, according to their characteristics.

Case study (A):

$$ESL = 21\times 1\times 1\times 0.9\times 1\times 1\times 0.8\times 1.1\times 1\times 0.9\times 0.95\times 1.1 \approx 16 \text{ years} \tag{6}$$

Case study (B):

$$ESL = 21\times 1\times 1.4\times 0.9\times 1\times 1\times 1\times 1\times 1\times 0.9\times 1.1\times 1.0 \approx 26 \text{ years} \tag{7}$$

Case study (C):

$$ESL = 21\times 1\times 1.1\times 1\times 0.775\times 1\times 0.8\times 1.1\times 1.15\times 0.95\times 0.95\times 1.1 \approx 18 \text{ years} \tag{8}$$

The graphical method allows estimating the service life of ETICS, portraying the physical degradation of these claddings systems, analysed during the fieldwork. Therefore, this method intends to translate reality and is applied to validate the results obtained by the factor method. For the three case studies analysed, the graphical method leads to an estimated service life of 14, 26 and 16 years, for case studies (A), (B) and (C), respectively, thus revealing very small deviations between the values estimated by the factor method and those determined by the graphical method. As discussed in this study, the proposed model presents consistent and credible results, functioning as a first approach to the modelling of the service life of ETICS.

The knowledge of the estimated service life of ETICS is fundamental for the planning and definition of maintenance plans. In fact, knowing the instant in which is necessary to intervene, it is possible to optimize resources, i.e. performing combined maintenance actions, minimizing the risk of failure of the claddings and reducing the costs related with the maintenance actions (avoiding the huge costs associated with urgent interventions). Furthermore, information on the number of replacements necessary of the ETICS system during the building's service life is crucial for the analysis of the environmental and economic impacts of the building's life cycle.

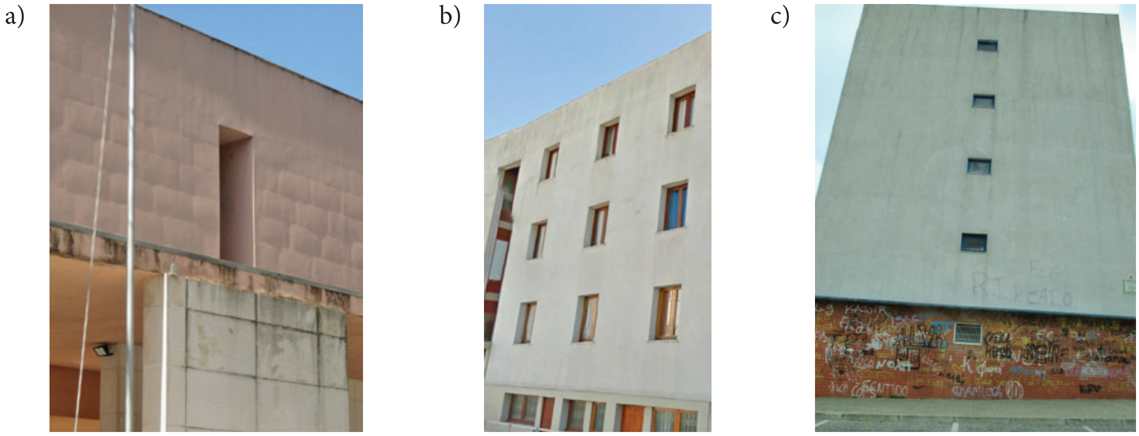

Figure 6. Case studies used to illustrate the application of the methodology proposed

Conclusions

The main objective of this study is the application of the factor method to predict the service life of ETICS. This method relies on the evaluation of the degradation state of ETICS systems, based on a field survey of 274 façades, located in Portugal. The proposed methodology consisted firstly on the identification of degradation patterns, modelling the degradation evolution of the overall sample over time. Subsequently, an evaluation of the degradation factors and their influence was carried out and the factor method was applied, considering the reference service life obtained for the sample, which was set at 21 years.

Finally, the indicative values of each weighting coefficient attributed to all the factors that were included in the durability formula were optimized through the analysis of four different scenarios and the results were examined based on various statistical indicators. It was concluded that the most favourable results (obtained in scenario 4) were achieved by adopting adjusted values obtained from an iterative optimization process that intends to approximate the values calculated through the factor method and the graphical method (which intends to translate the reality analysed in the fieldwork). Through this scenario, an estimated service life of 21 years for the overall sample was obtained, which is a similar value to the one achieved through the average degradation curve (approximately 20 years). It is important to note that the quantification of the durability factors is subjective because the attribution of standard values in all circumstances does not reflect a real situation nor does it seem like a reasonable option. In fact, the best results are achieved through iterative simulations which try to adjust the weighting coefficients for each variable to the physical reality, minimizing the deviations.

This study led to consistent and reasonable results for the majority of the durability factors analysed, reinforcing the notion that the factor method is an effective tool to estimate the service life of ETICS, despite its intrinsic constraints. However, this study can be seen as a first attempt to implement the factor method to the service life prediction of ETICS, making it necessary to identify possible ways to complement this study in order to circumvent and minimize the encountered limitations while improving the applied methodology. These limitations are associated fundamentally to two aspects: i) data collection (sample size and statistical significance of the data); and ii) model's calibration.

Although the sample size (274 case studies) is reasonable for the application of the methodology, it is considered that the existence of some factors not statistically significant limits obtaining conclusive results in some of the areas of research because they depend on the number of cases in the sample. Thus, it is proposed to include more claddings incorporating some of the underrepresented characteristics in the existing sample in order to validate and consolidate the data.

Another aspect that can be developed relates to the indication of the reference service life for construction elements under normal use conditions (particularly the components of the ETICS systems) by companies that produce and/or market these components. This information would be the key for the creation of a representative database that allows comparing and validating the results and the improvement of interventions associated with the implementation, management, operation and maintenance of buildings and their components, estimating their costs through information gathered from stakeholders in these processes.

The methodology used in this study can also be applied to new samples of buildings with other materials and also to other building components. Likewise, it would be interesting to explore a way of integrating discrete events (accidental impacts or vandalism) in later studies about the performance and durability of ETICS claddings.

For the application of the factor method, there are some aspects that can be developed, aimed at structuring and improving the results. One of the limitations of this methodology is its lack of sensitivity concerning the uncertainty resulting from the multiplicity of phenomena involved in the degradation of the claddings. In future studies, it would be interesting to integrate an approximate sensitivity analysis related to the risk and the uncertainty level associated with the durability factors and the degradation levels considered in this study.

Finally, the proposed model can be used in future researches on the durability of construction components and may contribute to aid the planning and improvement of the life-cycle management of ETICS claddings, allowing the definition of the most effective maintenance methods, reducing energy consumption and optimizing the use of technical and monetary resources.

Acknowledgements

The authors gratefully acknowledge the support of CERIS-ICIST from IST, University of Lisbon, and FCT, Foundation for Science and Technology.

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