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Methodology for service life prediction of window frames

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Abstract:

Window frames are an important element of buildings, with an enormous impact on their thermal performance and interior comfort conditions. Knowledge regarding the service life of window frames is extremely relevant, aiding the adoption of adequate solutions in the design and maintenance stages. This study proposes a methodology for the service life prediction of windows frames, based on the visual inspection of 182 case studies, in-use conditions, in which the degradation phenomena and various characteristics of window frames are surveyed. This information is converted into degradation curves, which express the evolution of the degradation of window frames over time, allowing estimating their service life and the influence of their characteristics on their durability. For aluminum and wooden frameworks, estimated service lives of 37.6 and 27.3 years are obtained. These results reveal that the window exposure conditions and the users' behaviors have a substantial impact on the degradation of window frames.

Keywords: Window frames, service life prediction, severity of degradation, degradation models.

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1. Introduction

Windows are one of the most important elements of a building. Window framing is designed to regulate indoor climate, through ventilation, and working as an entry to natural light, whilst preventing the entrance of foreign elements and protecting the living space from adverse conditions (Santos et al. 2017).

In the last decades, several studies have been performed, focusing on the influence of different factors on the energy efficiency of window frames, because of the importance of windows in the overall energy consumption of buildings, accounting for between 30-50% of the energy losses by transmission of the building envelope (Gustavsen et al. 2011). An adequate design of windows, regarding a correct dimension of its components, can result in between 21-24% of energy savings (Jaber and Ajib 2011). The various developments in this area, either life cycle analysis or the implementation of new materials in the thermal cut, have the same goal, to achieve more efficient systems, i.e. to work towards a sustainable future, in which energy consumption, maintenance and element replacements are minimized.

Window frames can be made of distinct materials, of which the most common are aluminum, wood, polyvinyl chloride (PVC) and iron/steel. The different window components play a central role on its performance, which means that the compatibility between the different materials must be ensured and their correct application guaranteed, since they directly affect the durability of the entire system.

This study addresses the durability and service life of window frames in real service conditions, through the analysis of different framing materials, specifically aluminum, wood and PVC, with different coatings, and in various exposure conditions. Following the methodology adopted in previous studies (Garrido et al. 2012; Ximenes et al. 2015; Silva et al. 2016; Serralheiro et al. 2017), this study proposes a model for service life prediction of window frames, based on the data collected through the visual inspection of 182 window frames, carried out during an extensive fieldwork, in which the different degradation phenomena and various characteristics of window frames are surveyed. The data is converted into degradation models, defined according to the factors that influence the deterioration of window frames, thus quantifying their impact on the window frames' service life. The results from the degradation models can provide useful information that can be used in the definition and optimization of maintenance plans, and different maintenance and repair plans could be defined according to the window frames' characteristics, thus allowing reducing the costs of these elements during their life cycle.

2. Background

The concept of service life is not unequivocal, and different authors present slightly different approaches to this concept. According to Masters and Brandt (1987), the service life of a building component is equal to the period of time during which all the essential requirements are met or exceeded, assuming there is periodic maintenance. ISO 15686-1: 2011, considered the most relevant reference on service life prediction of buildings and its components, defines service life as the period of time, after construction, in which the building and its elements meet or exceed the minimum performance requirements. Whether maintenance actions are implemented or not can play a crucial role in the buildings life cycle, since the performance of a building element over time can be influenced by the occurrence of maintenance actions, changing the values of the elements' service life and the related intervention costs.

In the literature, the service life prediction methods are divided in three main groups (Lacasse and Sjöström 2004): deterministic (e.g. factor and graphical method); probabilistic (e.g. Markov chains); and engineering methods (e.g. Failure modes effects analysis - *FMEA*).

The deterministic methods are based on the elements' degradation factors and their deterioration mechanisms. To each degradation factor, a relative importance or weight is assigned, which is later incorporated in formulas that express the action of the degradation mechanisms over time. Within deterministic methods, the factor method is the most widely used and recognized method, which was initially proposed by the Architectural Institute of Japan (AIJ 1993), in the guide to life planning of materials and components of buildings. Currently, this method is considered the general framework for service life estimation of building components, and is the methodology prescribed by the international standard for durability (ISO 15686: 2011).

This method is usually criticized due to the high dependence on deterministic factors, the great sensitivity to small variations of the data and the lack of instructions for determining the reference service life and the quantification of the modifying factors (Rudbeck 1999; Hovde 2005; Silva et al. 2016).

The graphical method is other example of a deterministic model, and it is the model used in this study. This empirical method is based on the definition of degradation curves, which are intended to describe the evolution of degradation of materials and components over time (Shohet and Paciuk 2004; Chai et al. 2014). In general, the quantification of the elements degradation is shown on the vertical axis, and the time since the elements implementation and the inspection date on horizontal axis. The type of curves used to model the building elements' condition varies according to the nature of the degradation phenomenon, and the best possible adjustment should be sought for the dataset present in the degradation graph (Shohet et al. 1999; Chai et al. 2014).

Unlike deterministic models, probabilistic or stochastic models include a probabilistic component in service life estimations, thus allowing a better understanding of the physical degradation phenomena. These methods are usually very complex and involve an extensive data collection in order to allow obtaining sufficiently representative samples, resulting in large disbursements of time and monetary cost, and their application is only advisable for large scale projects (Re Cecconi 2002).

Engineering methods seek to harmonize the two large groups of methods described, deterministic and probabilistic or stochastic. According to Moser (2004), the factor method can be used as an engineering method, by adopting probability distribution functions for each of the parameters included in the equation to estimate the building components' service life. This approach to the factor method allows implementing a greater detail (complexity) in the definition of the parameters that influence the element's service life.

3. Description of the field work

3.1 Description of the sample

The survey of the anomalies observed in window frames allows the definition of the degradation curves of the framework over time, by comparing the state of degradation of the various case studies analyzed. In this sense, a visual inspection is performed, involving the collection of the anomalies and the degradation mechanisms in the window frames, which result from the prolonged exposure of the element to service conditions. In this way, abnormal anomalies resulting from unpredictable phenomena such as vandalism, are excluded, since they cannot be modelled or predicted by a mathematical model. To achieve a better calibration of the model, it is important not only to analyze as many cases as possible, but also to obtain a sample with a wide range of ages and characteristics.

The field work was developed in Portugal, in which a total of 182 window frames were analyzed, 112 corresponding to aluminum, 45 to wood and 25 to PVC window frames. The owners of the dwellings were contacted to obtain relevant information regarding the age of the window frames, the dates and types of maintenance actions on the window frames, and the operating and cleaning habits. This information is extremely relevant, since the age of a window frame is defined as the period of time between its application (or the last intervention date) and the inspection date. The aluminum sample presents ages ranging between 1 and 39 years, homogeneously distributed. In the case of wood frames, most of the sample is concentrated between 31 and 40 years (54%), since this framing solution has been replaced by PVC or aluminum in more recent applications. A sample of 25 PVC window frames was also analyzed, with ages ranging from 1 to 13 years. The age and size of the PVC window frames sample can be explained by the relatively recent application of this type of window frames in Portugal, which do not allow obtaining unequivocal conclusions regarding the expected service life of these window frames.

3.2 Degradation phenomena in window frames

Due to the variety of materials implemented in each of the different window components, various degradation processes can be observed. There is a great diversity of components, of which the most important are glass, framework, sealings and metal fittings. In this sense, in this study, the anomalies in window frames are divided according to the affected component, meaning that three main anomalies groups can be specified: anomalies affecting the sealings; the material and coating of the framework; and the metal fittings (e.g. hinges, closing mechanisms).

Sealings play a crucial role on the windows' water tightness and air permeability, since its durability influence the overall performance of the entire system. Ageing of the sealing materials is characterized by the loss of their physical and chemical characteristics, thus leading to the occurrence of anomalies, which can lead to dimensional variation, loss of adhesion, loss of deformability and loss of material.

The degradation of the material and coating of the framework usually start with superficial anomalies in the coating, which, if not repaired, lead to the loss of the coating thickness and, ultimately, to its disappearance. These anomalies lead to the exposure of the framework material, causing an accelerated degradation and compromising its durability and aesthetic appearance. The anomalies that affect the framework depend on its material; however, although with different severities regarding the various framework materials, some anomalies occur in all the materials analyzed, such as: clearances between rim and span or between rim and sheet (excessive or insufficient); deformations; and accumulation of dirt/debris/biological growth.

The plastic components exposed to environmental agents show four main degradation mechanisms: photo degradation; thermo-oxidative degradation; hydrolysis degradation; and biological degradation (presence of microorganisms) (Andrady 2011). Plastic degradation manifests itself through the occurrence of surface anomalies such as: ultraviolet induced discoloration; occurrence of scratches; localized corrosion; and erosion.

For wooden frameworks, since timber is a putrescible material, it is strongly subjected to deterioration that leads to structural disintegration. There are several agents whose action results in the degradation of the wood, namely: atmospheric agents (e.g. moisture, ultraviolet radiation); and biological agents (e.g. rot fungi, molds and termites) (Sousa et al. 2016).

In metallic frameworks, the main mechanism of degradation is corrosion. Its occurrence and intensity in the metallic elements depend on several factors, such as: the constituent material; operating conditions (e.g. atmospheric humidity, rainfall); and the aggressiveness of the environment to which it is exposed (e.g. industrial zone, maritime) (Howard and Burgess 2007).

The possible causes for malfunction or damage to metal fittings are: improper handling of moving parts or mechanisms; inadequate choice of profile, materials, and geometry or frame system, as a function of window span; use of inexperienced or unskilled labor; vandalism; and presence of water (enabling corrosion).

Although glass represents a large percentage of the area of the window span, due to the good characteristics and durability of glass, this element does not show a great variety of anomalies, the ones more frequently observed are related to condensations on the surface of the glass or its fracture. The occurrence of the first type of anomalies may lead to the degradation of the frame material (corrosion and rotting), development of microorganisms, loss of insulation capacity, as well as negatively affecting the aesthetic aspect of the window frame. In the case of fractures, the consequences are severe as they compromise the water tightness of the system, in addition to the risks associated with the safety of the building occupants.

To simplify the process of quantifying the dimensions of the various elements of the window frame, without compromising the accuracy and representativeness of the methodology applied in this study, the following criteria were adopted:

- The evaluation of the dimensions of the various elements, except for metal fittings and the related anomalies, is carried out only on the exterior of the building, since it is exposed to the various environment agents;
- The framework and sealings are quantified linearly; this choice is advantageous since one of the dimensions of these elements is substantially bigger; moreover, in this case the calculation of areas requires extraneous rigor, making the process excessively slow and not operative;
- Metal fittings are unitarily quantified, i.e. the anomalies are accounted in terms of number of mechanisms affected.

Concerning the anomalies affecting the sealing (Fig. 1a), in this study, a great percentage of the window frames inspected showed superficial degradation of the sealings, and in the case of wooden frames, deterioration of the putty seal coating (around

65%). The wooden frame putty seal is the material with the highest frequency of detachment/discontinuity of the sealing material and absence of sealing material, which promote both air infiltration and water ingress (Howard and Burgess 2007).

Regarding the anomalies of the framework material and coating (Fig. 1b), aluminum and PVC window frames show a low incidence of anomalies. Wooden frames show a higher occurrence of anomalies in the coating; 91% of the wooden frames inspected present detachment or absence of the coating, which allows the development of anomalies in the frame material such as the aging and deterioration of wood, which occurs in 38% of the wooden frames inspected. There are also registered 32 (71%) cases of open joints/gaps in wooden frames, which can be considered an anomaly that compromises the watertightness of the window system.

4. Service life prediction model

The model proposed in this study is based on the methodology established by Gaspar and de Brito (2011), considering the specific characteristics of window frames, and data obtained during the fieldwork. This model expresses the global degradation of a building element through a numerical index, which considers the anomalies detected in the element under analysis and their severity, based on their effect on the element's durability.

In this study, the degradation levels are associated with the percentage of the component affected by the anomaly, according to the methodology proposed by Gaspar and de Brito (2011). The classification is made based on five levels of degradation, where level A represents an element with no visible degradation and level E corresponds to a severe degradation condition of the element, in which even minimum levels of water tightness and operability are compromised. Similarly to other studies (Gaspar and de Brito 2011; Silva et al. 2016; Serralheiro et al. 2017), the fourth degradation level, equivalent to level D, is considered as the end of service life of the window frames.

Therefore, after reaching the degradation level D or above (which corresponds to a severity of degradation of 20%), the window frames require an intervention, in order to re-establish the necessary characteristics to meet the performance requirements. Based on the literature and through the analysis of the degradation phenomena in window frames, in this study, the degradation levels are established as shown in Table 1.

The estimation of the window frames degradation ($S_{w,wf}$ - the severity of degradation for window frames) is obtained as shown in Equation (1), which is obtained through the sum of the ratio between the weighted degraded dimension of the window frame component and the total dimension of the component with the highest level of degradation.

$$S_{w,wf} = \frac{\Sigma(L_g \times k_n \times k_{a,n})}{L_{T,g} \times k_{max,g}} + \frac{\Sigma(L_f \times k_n \times k_{a,n})}{L_{T,f} \times k_{max,f}} + \frac{\Sigma(L_{mf} \times k_n \times k_{a,n})}{L_{T,mf} \times k_{max,mf}} = \frac{E_{w,p}}{k_{max}} \quad (1)$$

Where:

$S_{w,wf}$ - severity of the window frame degradation, in %;

L_g - dimension of the sealing material affected by anomalies, in cm;

L_f - dimension of framework material and coating affected by anomalies, in cm;

L_{mf} - number of metal fittings affected by anomalies;

k_n - multiplication factor for anomaly n, as a function of its degradation level (k varies between 0 and 4);

$k_{a,n}$ - weighting coefficient corresponding to the relative weight of the detected anomaly; $k_{a,n} \in R+$; $k_{a,n} = 1$ if there is no specification;

$L_{T,g}$ - overall dimension of the sealing material, in cm;

$L_{T,f}$ - overall dimension of the framework, in cm;

$L_{T,mf}$ - total number of metal fittings;

$k_{max,g}$ - weighting constant, equal to the highest level of degradation possible for sealing material anomalies (4);

$k_{max,f}$ - weighting constant, equal to the highest level of degradation possible for framework material and coating anomalies (4);

$k_{max,mf}$ - weighting constant, equal to the highest level of degradation possible for metal fittings anomalies (4);

k_{max} - sum of the weighing constants, corresponding to the highest possible level of degradation (4+4+4, sealing material, framework material and coating, and metal fittings anomalies);

$E_{w,p}$ - window frame weighted degradation level.

4.1 Relative importance of the anomalies

As proposed by other authors (Shohet and Paciuk 2004; Serralheiro et al. 2017), in this study, a weighting coefficient is adopted to establish a relative importance between anomalies (Table 2). Different anomalies can affect the same extent of the window frames, but each anomaly causes a different damage and presents a different severity for the overall degradation of the window framing system. The weighting coefficients are defined considering: i) how a given anomaly affects the compliance with the minimum requirements of the element; ii) its tendency to cause new anomalies or increase the propagation speed of existing ones; iii) and its repair cost, since this may also influence the service life of the element. The repair costs were determined for a standardized window, considering the prices practiced by some companies and price simulators. In the definition of the weighting coefficients, the following assumptions were adopted:

- The accumulation of debris has a lower impact on the overall degradation condition of the window frames, and therefore a weighing coefficient of 0.1 is adopted;
- The color change/superficial deterioration of the seal is a superficial anomaly that indicates the beginning of the chemical alteration of this component; therefore, the repair of this anomaly can be encompassed by the replacement of

the seal, with a related cost of €30 per window. However, due to the low influence of this anomaly on the window frames' performance, seals are rarely replaced to simply repair this anomaly, and a weighing coefficient of 0.3 is adopted. In wooden frames, the deterioration of the coating of the putty seal promotes the deterioration of the window frame, compromising its water tightness; in this sense, despite the lower cost of repair (€10 to €15 per window), the value adopted for the weighting coefficient for this anomaly is 0.5;

- Biological colonization is usually removed through cleaning actions using biocides or similar treatments. Nevertheless, biological colonization is not easily eliminated and can reappear. In sealing materials and wooden frames, a weighting coefficient of 0.6 is assigned, since these elements are more susceptible to the degradation agents, and for aluminum frameworks a weighting coefficient of 0.4 is established, since these window frames are less affected by the presence of biologic colonization;
- The corrosion of the framework material is a specific anomaly of the iron/steel and aluminum window frames, and the repair of this anomaly is a challenging and time-consuming task, only recommended if the affected areas are small. Due to the impact of this anomaly in the aluminum window frames, a weighting coefficient of 0.6 is assigned;
- The aging of the framework material occurs in wooden and PVC window frames and corresponds to the deterioration of the framework material, being of comparable importance to corrosion in iron/steel and aluminum frames. This anomaly is mainly identified in wooden window frames. The repair of this anomaly encompasses the treatment of the affected zone and application of a repainting. A weighting coefficient of 0.6 is assigned for PVC window frames

and 1 for wooden window frames, thus reflecting the greater influence of this anomaly for the deterioration of wooden window frames;

- The deformation of the framework may reflect a high level of degradation of the frame, depending on the extension and the affected element. The repair of this anomaly is difficult and may even include the replacement of the element; in this sense, a value of 0.8 is adopted;
- Other anomalies, such as detachment/discontinuity and absence of the sealing material in aluminum, or rot in wooden frames, are extremely harmful anomalies, seriously affecting the framework's durability e and its service life, thus presenting the highest weighting values. In these situations, the weighting coefficients are higher than 1, since the repair of these anomalies requires the replacement of the degraded elements.

4.2 Degradation curves

The degradation curves obtained for the 112 aluminum, 45 wooden and 25 PVC window frames inspected, is shown in Fig. 2. The degradation curves are obtained through a simple regression analysis, in which a regression trend is adjusted to the scatter of points that represent the sample under analysis. This regression analysis provides a mathematical equation and a degradation curve that establish the relationship between the dependent variable (the severity of degradation) and the independent variable (the age of the window frames). In this study, different degradation patterns are obtained, as described by Shohet et al. (1999), reflecting the various degradation phenomena observed on the element under analysis. The degradation pattern obtained for aluminum framework is "S" shaped, reflecting an early stage where there is a noticeable presence of anomalies, usually consisting of surface anomalies, followed by a period in which the evolution of the degradation appears to stabilize, and finally, an accelerated degradation phase in which there is an intensification and synergy of the degradation phenomena.

For wooden and PVC framework, the degradation curve has a convex shape, specifically a potential curve, which is associated with an initially slow degradation phenomena, but whose effects are cumulative. This degradation pattern reflects the greater susceptibility of wooden frameworks to the degradation agents, since the deterioration of the coating rapidly affects the overall performance of the frame.

The square of the Pearson product correlation coefficient (or determination coefficient - R^2) evaluates the proportion of the variation of the dependent variable that can be explained by the model, i.e. the degree to which observed reality can be explained by the regression model (Nagelkerke 1991). This coefficient can vary between 0 (zero correlation) and 1 (perfect correlation), where the obtained values of 0.79, 0.89 and 0.72, for aluminum, wood and PVC frames, respectively, reveal a strong correlation between the degradation curve and the sample analyzed. These results also reveal that 79% and 89% of the variability of the window frames degradation, for aluminum and wooden frames, respectively, can be explained by their age (the only variable included in the model).

Therefore, some of the variability of the severity of degradation is explained by other characteristics of window frames. In fact, the service life of window frames also depends on the material applied, the environmental exposure conditions and the type and periodicity of the maintenance carried out (Asif et al. 2005). Therefore, to extend the knowledge of the influence of different factors on the degradation of window frames, various degradation curves are defined, according to the characteristics of the window frames analyzed (Fig. 3 to 7). However, due to the sample's size, some characteristics appear in few case studies, and thus the results obtained must be analyzed with some caution, regarding their statistical significance. In the case of PVC frames, the ages and size of the sample gathered during the fieldwork do not allow obtaining unequivocal conclusions regarding the evolution of degradation of these window frames over time and according to their characteristics. In this sense, further analyses of the influencing factors for the degradation of window frames are only performed for aluminum and wooden frames.

The use of shading devices allows protecting window frames against weather agents, in exchange for the loss of sunlight entering in the interior of the house, which is why they are especially used at night and in hot seasons. The sample is divided according to the number of hours in which the shading devices are closed (protecting the window frames from the weathering agents) (Fig. 3): i) 10 hours or more per day; and ii) less than 10 hours per day. As expected, window frames with a higher number of hours of protection, degraded at a slower pace, with higher estimated service lives.

Fig. 4 presents the analysis of the evolution of degradation of window frames according to periodicity of the cleaning actions performed. The sample is divided in two categories: i) window frames that are subjected to cleaning actions every week (or even more frequently); and ii) window frames with a less frequent cleaning actions. The absence or a low frequency of the cleaning actions contribute to the occurrence of various anomalies, thus leading to a faster degradation of the window frames (Santos et al. 2017). In our sample, wooden and aluminum frames with a lower frequency of maintenance actions tend to deteriorate faster, reaching sooner the end of their service life. For aluminum frames, although the curve of less regular maintenance actions (> weekly) showed an initially faster degradation, as expected, the two curves eventually converged. This can be explained, since some anomalies, which eventually occur over time due to environmental degradation, cannot be repaired or mitigated with simple cleaning actions. In this sense, cleaning operations have no significant impact on the degradation of aluminum window frames in the long term (> 30 years).

Regarding exposure conditions (Fig. 5), the span is classified as exposed or protected, where in the second case the window can benefit from greater protection against wind and solar radiation exposure. As expected, window frames classified as exposed reach the end of their service life earlier. In the case of protected wooden frames, the lower value of the determination coefficient may be explained by the lack of case studies with ages under 21 years.

Figure 6 presents the degradation curves obtained according to window frames' orientation. In Portugal, the North and West orientations present greater exposure to the actions of wind and rain and, therefore, humidity. On the other hand, the southern-oriented window frames are exposed to a greater amount of solar radiation, leading to a greater thermal gradient (Gaspar and de Brito 2008).

For aluminum frames (Fig. 6a), the northern orientation has the fastest degradation of the window frames, while wooden frames (Fig. 6b) facing West and South reach first the end of their service lives. Although high determination coefficients are obtained for wooden frames, the North orientation curve is based on 4 points only, and therefore does not allow obtaining unequivocal conclusions.

To evaluate the influence of the distance from the sea on window frames' degradation (Fig. 7), two intervals are considered: i) more than 5 km from the sea; and ii) less than 5 km from the sea. By analyzing the curves, window frames located less than 5 km from the sea present a faster degradation path. Nevertheless, when the sample is divided according to the distance from the sea, the ages are not uniformly distributed along the degradation curve, and therefore, the results must be analyzed with some caution.

5 Discussion of the results

The service life of window frames is evaluated by determining the instant after which these elements reach a degradation condition, considered as inadmissible. In this study, the end of the service life of the element under analysis corresponds to a severity of degradation of 20%. In Fig. 8, an aluminum window frame with a $S_{w,wf}$ equal to 20.7%, and a wooden window frame with a $S_{w,wf}$ equal to 21.5% are shown, illustrating the overall degradation that portrays the end of service life of window frames. Therefore, the estimated service life of the window frames is thus calculated through the intersection of this limit with the overall degradation curve.

The most severe anomalies, with higher impact for establishing the end of service life of window frames, are: i) for aluminum frames, the deterioration of sealings and mechanisms; and ii) for wooden frames, the absence of the putty seal in the lower rim, where there is more accumulation of rainwater, the aging of the wood also in the lower rim and the existence of clearances between the movable and fixed rim.

In a simplified approach, the standard for the durability and the different European EPD operators (PCR 2011) refer that window frames must present an estimated service life of at least 30 years. However, the service life of the window frames varies significantly according to the type of the material used. Brown et al. (1999) proposed an estimated service life of 45 years for aluminum-coated timber, 40 years for aluminum, 35 for timber and 22.5 for PVC. Citherlet et al. (2000) proposed an estimated service life of 45 years for aluminum and wood frames, and 30 years for PVC. A survey performed by Asif et al. (2005) indicates an estimated service life for window frames of 43.6 years for aluminum, 39.6 for wood and 24.1 for PVC.

In this study, for aluminum frameworks, an estimated service life (ESL) of 37.6 years is obtained, which agrees with the results obtained by Re Cecconi et al. (2017), where the ESL values for this type of framework varies between 30 and 42 years, and with the HAMP (Housing Association Property Mutual Ltd.) manual, where the ESL for aluminum and wood frameworks is 35 years, when properly and regularly maintained.

Concerning wooden frameworks, an ESL of 27.3 years is obtained, which is lower than values proposed in other works. This can be justified by the fact that the inspected window frames are not subjected to regular repairs or interventions. According to a survey performed by Asif et al. (2002), wooden frameworks are the type of framework that requires the highest number of such actions during their life cycle, which means that the absence of regular maintenance actions strongly reduces the service life of these window frames.

Fig. 9 presents the estimated service life (ESL) of window frames, according to their various characteristics. The durability and service life of window frames are strongly conditioned by their exposure to environmental and surrounding conditions:

- The most substantial differences in the ESL are obtained in the window span orientation, for both aluminum and wooden frameworks;
- Aluminum frames are more negatively affected by the northern orientation, indicating that these window frames are more susceptible to degradation mechanisms related with the presence of humidity;
- Wooden frames are more negatively affected by the southern and west orientations, which reveal that these frames are adversely affected by high thermal gradients and the presence of moisture, which is in accordance with the evaluation of the degradation factors of the wooden window frames made by de Brito et al. (2006);
- Concerning the distance from the sea, aluminum frames are more affected by the exposure to sea salts spray than wood frames, since aluminum windows have a tendency to corrode under marine environments, while wooden frames tend to remain unaltered;
- These results are in accordance with other studies and accelerated tests performed to aluminum and wood frames (Asif et al. 2005; Howard and Burgess 2007), which reveal that aluminum frames are more prone to degradation due to presence of humidity and sea salts, while wood frames are

more susceptible to ultraviolet radiation, humidity and the presence of biological agents.

Moreover, the users' behaviors, namely related with the use of shading devices, and the frequency of cleaning actions also have a substantial impact on the degradation window frames. The combination of more favorable conditions, to increase the window frames' service life, corresponds to the use of shading devices for at least 10 hours per day and the adoption of a weekly cleaning frequency.

6 Conclusions

In this study, a methodology to estimate the service life of window frames is proposed, based on the evaluation of the degradation condition of 182 window frames, under real conditions of use and environmental exposure. The degradation condition of window frames, observed during a fieldwork survey, is translated into a numerical index, which considers the anomalies that occur in window frames, their extent and severity. This numerical index is used to establish graphical degradation models, which represent the evolution of the degradation condition of window frames over time.

Different materials face different degradation mechanisms over their service life due to the environmental exposure conditions. In this sense, in this study, the service life of window frames is evaluated through the analysis of the influence of different characteristics on their degradation phenomena. The results obtained reveal that wood window frames seem to be adversely affected by high thermal gradients and the presence of moisture, being more susceptible to chemical and biological degradation. In the case of aluminum frames, window frames facing North and closer to sea present a faster degradation pace, due to the presence of moisture and sea salts, which promotes the occurrence of corrosion in this window frames' material. Use and maintenance conditions also influence the degradation of aluminum and wood window frames, revealing that the adequate use of shading devices and periodic cleaning actions can prolong the service life of window frames.

The knowledge regarding the durability and service life of window frames is extremely relevant for a better evaluation of the overall costs of these elements during the buildings' life cycle. Moreover, the results of the estimated service life of aluminum and wooden window frames under real conditions can be useful for designers and stakeholders, to compare different technical solutions and determine the ideal periods for maintenance and repair operations.

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FIGURE CAPTIONS

Fig. 1. Anomalies observed during the fieldwork: (a) affecting the sealing; (b) in the metal fittings; (c) degradation of the material and coating of the framework

Fig. 2. Degradation curves obtained from the total of 182 window frames inspected in the fieldwork

Fig. 3. Degradation curves according to the use of shading devices: (a) aluminum; (b) wood

Fig. 4. Degradation curves according to the frequency of cleaning actions: (a) aluminum; (b) wood

Fig. 5. Degradation curves according the window span exposure: (a) aluminum; (b) wood

Fig. 6. Degradation curves according to window span orientation: (a) aluminum; (b) wood

Fig. 7. Degradation curves according to distance from the sea: (a) aluminum; (b) wood

Fig. 8. Illustrative example of window frames near the end of their service life (a) aluminum framework, (b) wooden framework

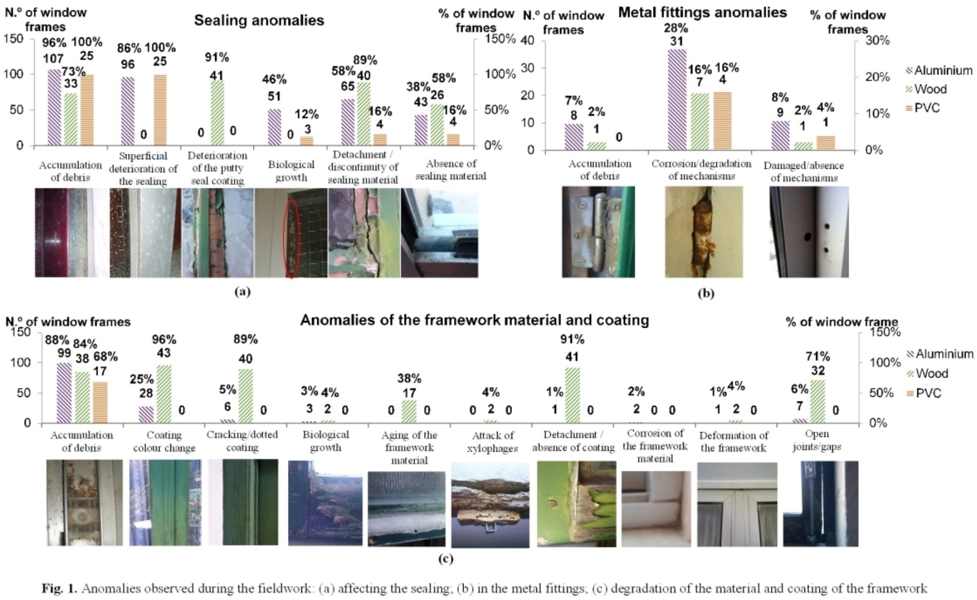

Fig. 1. Anomalies observed during the fieldwork: (a) affecting the sealing; (b) in the metal fittings; (c) degradation of the material and coating of the framework

176x109mm (300 x 300 DPI)

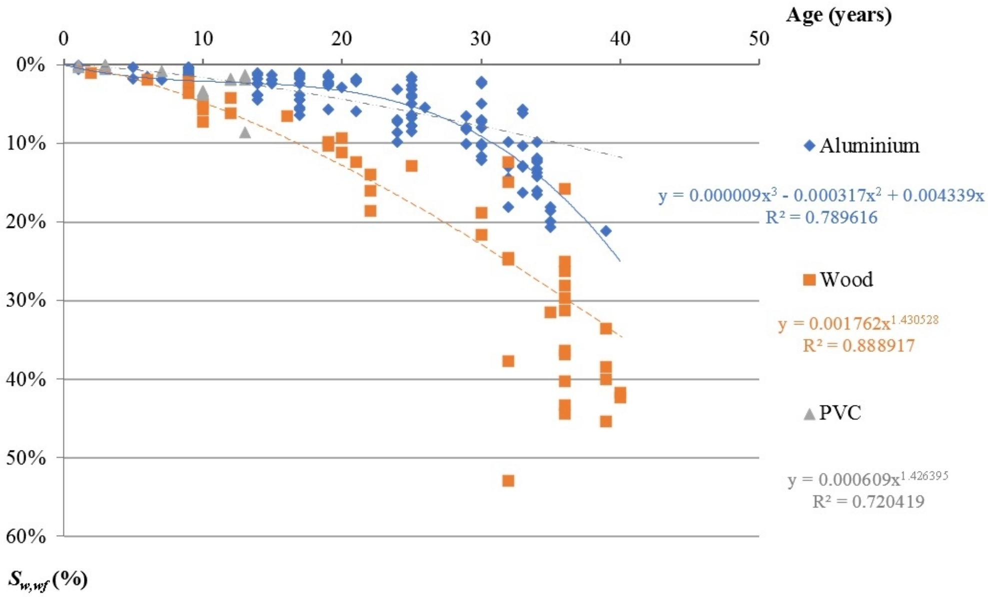

Fig. 2. Degradation curves obtained from the total of 182 window frames inspected in the fieldwork

Fig. 2. Degradation curves obtained from the total of 182 window frames inspected in the fieldwork

88x64mm (300 x 300 DPI)

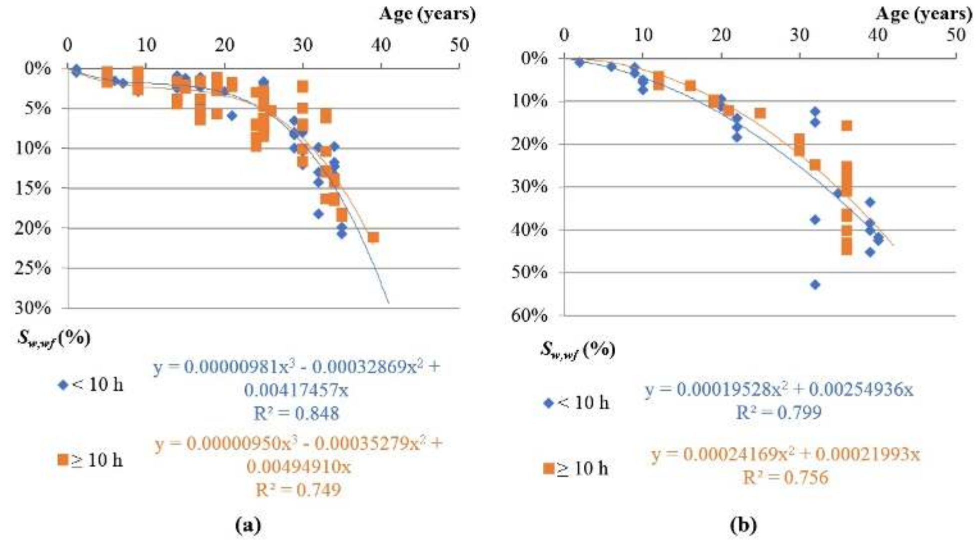

Fig. 3. Degradation curves according to the use of shading devices: (a) aluminum; (b) wood

Fig. 3. Degradation curves according to the use of shading devices: (a) aluminum; (b) wood

101x64mm (300 x 300 DPI)

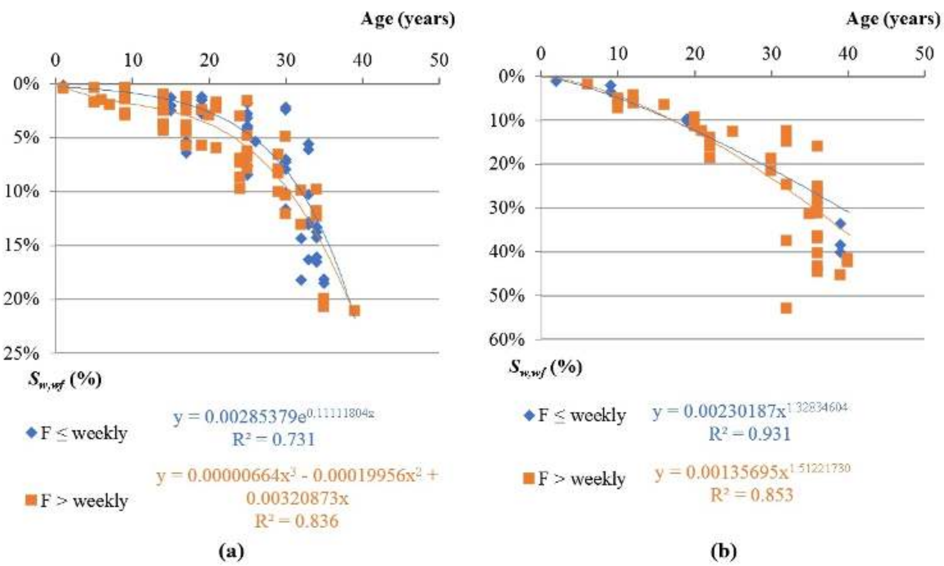

Fig. 4. Degradation curves according to the frequency of cleaning actions: (a) aluminum; (b) wood

Fig. 4. Degradation curves according to the frequency of cleaning actions: (a) aluminum; (b) wood

103x64mm (300 x 300 DPI)

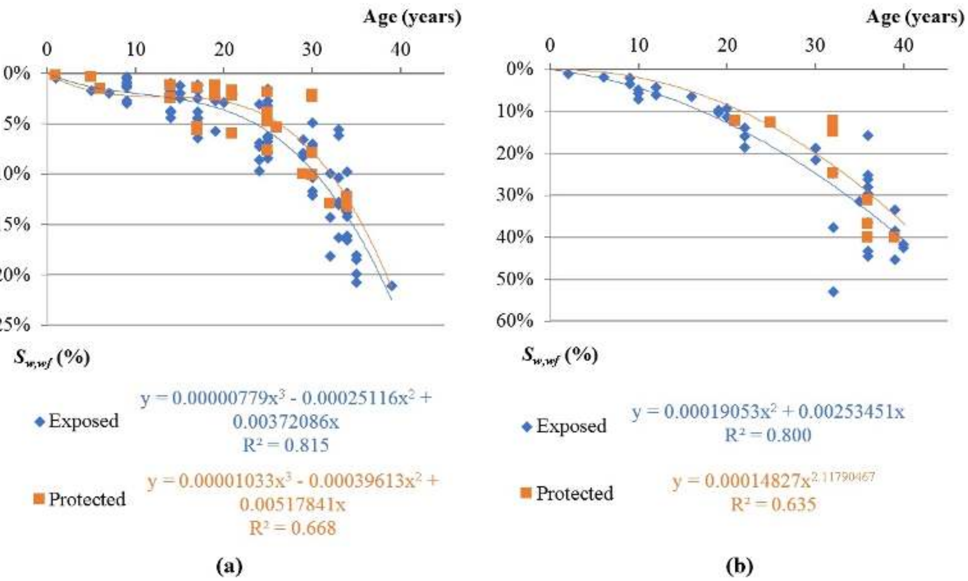

Fig. 5. Degradation curves according the window span exposure: (a) aluminum; (b) wood

Fig. 5. Degradation curves according the window span exposure: (a) aluminum; (b) wood

100x64mm (300 x 300 DPI)

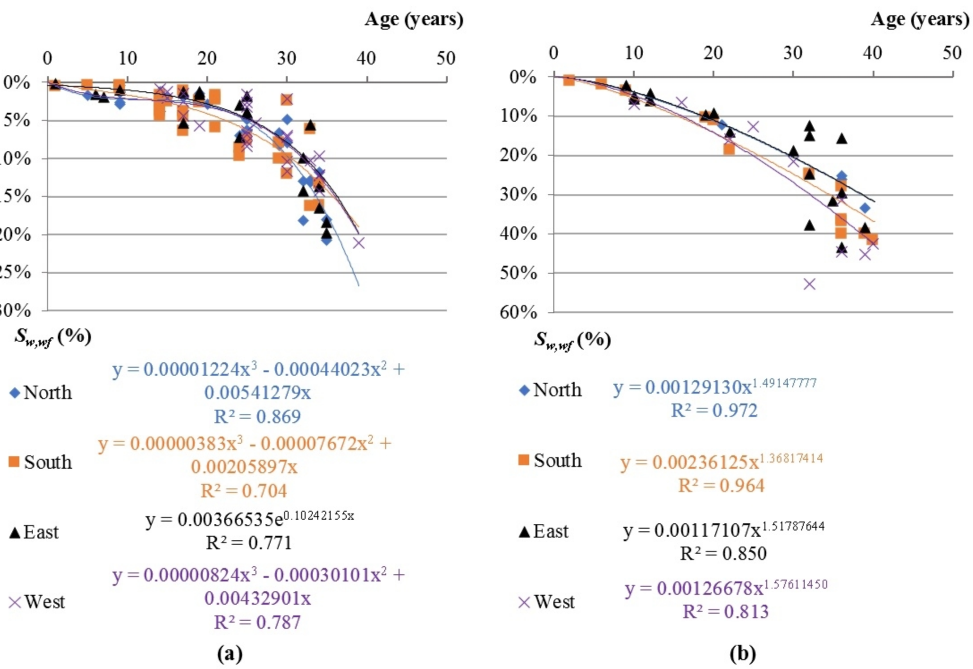

Fig. 6. Degradation curves according to window span orientation: (a) aluminum; (b) wood

Fig. 6. Degradation curves according to window span orientation: (a) aluminum; (b) wood

94x66mm (300 x 300 DPI)

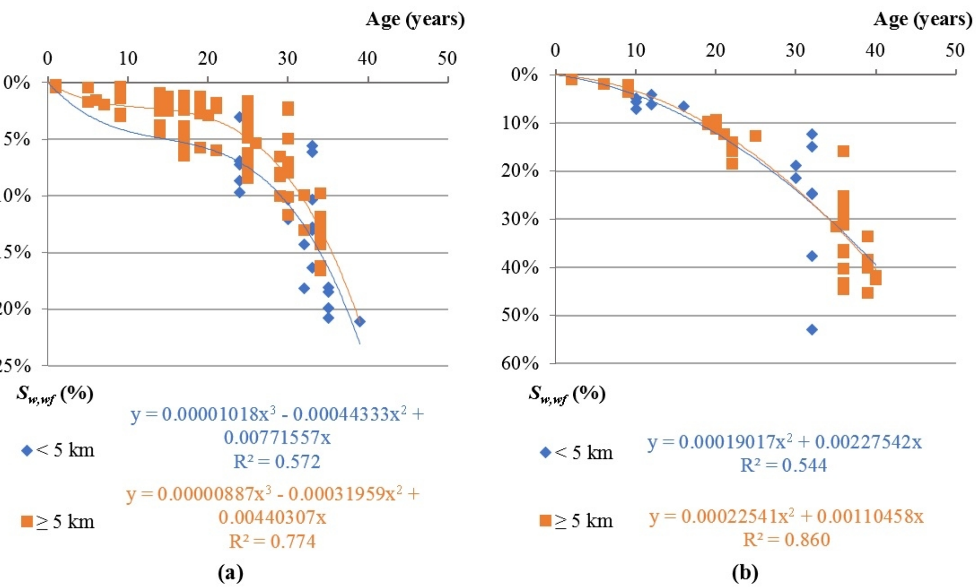

Fig. 7. Degradation curves according to distance from the sea: (a) aluminum; (b) wood

Fig. 7. Degradation curves according to distance from the sea: (a) aluminum; (b) wood

94x64mm (300 x 300 DPI)

(a) Aluminum framework

(b) Wooden framework

Fig. 8. Illustrative example of window frames near the end of their service life (a) aluminum framework, (b) wooden framework

Fig. 8. Illustrative example of window frames near the end of their service life (a) aluminum frame-work, (b) wooden framework

96x64mm (300 x 300 DPI)

Table 1 - Proposed degradation levels for window frames

Degradation level	Anomalies group	Anomalies description	% of component affected
Level A (Very good) $S_{w,wf} \leq 1\%$	-	No visible degradation	-
Level B (Good) $1\% < S_{w,wf} \leq 10\%$	Sealings	Accumulation of debris	> 20%
		Color change/superficial deterioration of the sealing [I/S] [A] [PVC]	≤ 10%
	Material and coating of the framework	Accumulation of debris	> 20%
		Coating color change	≤ 10%
		Cracking/dotted coating	≤ 10%
		Detachment/absence of coating	≤ 10%
	Metal fittings	Accumulation of debris	> 20%
Level C (Slight degradation) $10\% < S_{w,wf} \leq 20\%$	Sealings	Color change/superficial deterioration of the sealing [I/S] [A] [PVC]	> 10% to ≤ 50%
		Deterioration of the coating of the putty seal [W]	> 10% to ≤ 20%
		Biological growth	≤ 15%
	Material and coating of the framework	Coating color change	> 10% to ≤ 50%
		Cracking/dotted coating	> 10% to ≤ 50%
		Detachment/absence of coating	> 10% to ≤ 50%
		Biological growth	≤ 15%
	Metal fittings	-	-
Level D (Moderate degradation) $20\% < S_{w,wf} \leq 40\%$	Sealings	Color change/superficial deterioration of the sealing [I/S] [A] [PVC]	> 50%
		Deterioration of the coating of the putty seal [W]	> 20% to ≤ 40%
		Biological growth	> 15% to ≤ 30%
		Detachment/discontinuity of sealing material *	> 10% to ≤ 30%
	Material and coating of the framework	Coating color change	> 50%
		Cracking/dotted coating	> 50%
		Biological growth	> 15% to ≤ 30%
		Detachment/absence of coating	> 50%
		Corrosion of the framework material [I/S] [A] *	> 10% to ≤ 20%
		Attack of xylophages [W] *	≤ 10%
		Attack of rot fungi/mold [W] *	≤ 10%
		Aging of the framework material [W] [PVC]	> 10% to ≤ 20%
		Deformation of the framework *	> 10% to ≤ 30%
		Open joints/gaps *	> 10% to ≤ 30%
	Metal fittings	Corrosion/degradation of mechanisms *	> 20% to ≤ 40%
		Damaged/absence of mechanisms *	> 20% to ≤ 40%
Level E (Severe degradation) $S_{w,wf} > 40\%$	Sealings	Deterioration of the coating of the putty seal [W]	> 40%
		Biological growth	> 30%
		Detachment/discontinuity of sealing material	> 30%
		Absence of sealing material	> 10%
	Material and coating of the framework	Biological growth	> 30%
		Corrosion of the framework material [I/S] [A]	> 20%
		Attack of xylophages [W] *	> 10%
		Attack of rot fungi/mold [W] *	> 10%
		Aging of the framework material [W] [PVC]	> 20%
		Deformation of the framework *	> 30%
		Open joints/gaps *	> 30%
	Metal fittings	Corrosion/degradation of mechanisms *	> 40%
		Damaged/absence of mechanisms *	> 40%

[A] - Applicable to aluminum framework; [I/S] - Applicable to iron/steel framework; [W] - Applicable to wooden framework; [PVC] - Applicable to PVC framework
***If the anomaly results in insufficient sealing (compromising water tightness or air permeability) or in operation problems of the frame, the degradation level is increased by one.**

Table 2 - Weighting coefficients according to the type of anomaly

Anomalies in the sealing material

Accumulation of debris	Color changes/superficial deterioration of sealing material	Deterioration of the coating of the putty seal	Biological growth	Detachment/discontinuity of sealing material	Absence of sealing material
0.1	0.3	0.5	0.6	1.5	2.0

Framework and coating anomalies

Accumulation of debris	Coating color change	Cracking/dotted coating	Detachment/absence of coating		Biological growth		Corrosion of the framework material
0.1	0.2	0.3	0.5 [I/S] [A] [PVC]	1.0 [W]	0.4 [I/S] [A] [PVC]	0.6 [W]	0.6

Attack of xylophages	Attack of rot fungi/mold	Aging of the framework material		Deformation of the framework	Open joints/gaps	
1.5	1.5	1.0 [W]	0.6 [PVC]	0.8	1.0 [I/S] [A] [PVC]	1.2 [W]

Metal fittings anomalies

Accumulation of debris	Corrosion/degradation of mechanisms	Damaged/absence of mechanisms
0.1	0.3	1.0

[A] - Applicable to aluminum framework; [I/S] - Applicable to iron/steel framework; [W] - Applicable to wooden framework; [PVC] - Applicable to PVC framework