Service life prediction of window frames

Daniel Vítor Fernandes

Instituto Superior Técnico

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1. Introduction

This dissertation intends to develop a methodology to estimate the service life of window frames, following a research line, previously developed for façades by Gaspar (2002, 2009), Silva *et al.* (2011), and Serralheiro *et al.* (2017), among others, with the required adjustments of the calculation methods.

The methodology developed in this study is based on the data collected through the visual inspection of window frames, carried out during an extensive fieldwork survey, in which the different degradation phenomena and various characteristics of window frames are surveyed. The data is then analysed and converted into degradation models, which represent the loss of performance of window frames over time. The results from the degradation models can provide useful information for the definition and optimization of maintenance plans, allowing the reduction of the costs of these elements during their life cycle.

2. Service life definition

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 exceed, assuming there is periodic maintenance. Whether these 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 (Flores, 2002). Gaspar (2002) refers that the end of a building service life may occur due to functional obsolescence, loss of economic performance, and physical degradation of its key materials. Moser (1999) states that the end of service life is dependent on safety, functional or aesthetic criteria, in which the last criteria constitutes a parameter of difficult evaluation, since the definition of a minimum performance level is associated with the interpretation and expectations of the stakeholder.

To standardise this concept, ISO 15686-1: 2000 was created, and later updated in 2011; this standard is currently considered the most relevant reference for service life prediction of buildings and components. This standard defines service life as the period of time, after construction, in which the building and its elements meet or exceed the minimum performance requirements.

3. Description of the window components

The window is one of the most important non-structural element of a building, connecting the exterior and interior environments. Window framing is designed to regulate indoor climate, through ventilation, and serve as an entry to natural light, whilst preventing the entrance of foreign elements and protecting the living space from adverse conditions. According to Mateus and Bragança (2006), 25% of the energy consumption of residential buildings is allocated to indoor climate regulation and Gustavsen et al. (2011) state that windows account for between 30% and 50% of the energy losses by transmission of the building envelope.

Window frames can be made of distinct materials, which the most common are aluminium, wood, PVC and iron/steel. Currently, iron/steel widow frames are, almost exclusively, implemented in cases of special architectonic/artistic importance, or in scenarios of rehabilitation of historical components.

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. Although there is a great diversity in the components, the most important are glass, framework, gaskets and metal fittings.

3.1 Characterization of the anomalies

The anomalies in window frames can be divided according to the affected component, meaning that three main anomalies groups can be specified: anomalies affecting the gaskets; the material and coating of the framework; and the metal fittings (e.g. hinges, closing mechanisms).

The gaskets play a crucial role in the windows' wind and water tightness, since its durability and performance 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 analysed, such as: clearances between rim and span or between rim and sheet (excessive or insufficient); deformations; and accumulation of dirt/debris/biological growth.

In the case of 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) (Fontinha, 2002).

For the wooden framework, since it 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, moulds and termites) (Sousa *et al.*, 2003).

In the case of PVC window frames, 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; appearance of scratches; localized corrosion; and erosion. The evolution of such degradation mechanisms may lead to weakening of the mechanical characteristics of the window frame, such as the decrease of flexure, tension and impact resistance (Real, 2001).

The metal fittings, hinges and closing mechanisms are responsible for allowing the operation of the various moving elements. In this sense, the deterioration or damage of such components limits the window operation, compromising the functionality of the entire system. 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 labour; 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 it compromises the watertightness of the system, in addition to the risks associated with the safety of the building occupants. Glass-related anomalies, despite being catalogued, are not studied, since the most likely causes of their occurrence are associated with discrete phenomena, difficult or even impossible to predict, making it unreasonable to model such events during the life cycle of a window frame.

4. Fieldwork

The main purpose of the fieldwork is to perform a survey of the anomalies present in window frames. In order to fully understand the impacts of such anomalies in the degradation process, it is necessary to define levels of degradation for window frames, in regard to each group of anomalies, as well as taking into account the different materials. The data collected during the fieldwork was properly analysed, resulting in a total of 182 window frames inspected.

4.1 Levels of degradation

Shohet *et al.* (2003) propose a methodology for defining the maintenance priorities of building components, based on their expected degradation. For that purpose, a scale with five levels of degradation was established for window frames, in which the condition 100 (very good) represents a near perfect overall state of the window frame, as opposed to the condition 20 (dangerous), where there is severe mechanical damage and the watertightness is compromised. This study is the basis for the definition of the degradation levels of the anomalies groups considered for window frames. Moreover, in this study, the degradation levels are associated with the percentage of the component affected by the anomaly, making the system more in line with the methodology proposed by Gaspar (2009). Therefore, the classification is made according to five levels of degradation, where level 0 represents an element with no visible degradation and level 4 corresponds to a severe degradation of the element, in which even minimum levels of watertightness and operability are compromised (Tables 1 to 3).

Due to some anomalies, such as open joints and gaps, with low percentages of affected component, but possibly resulting on a high impact in the window functionality (e.g. loss of air or watertightness), Table 4 shows the changes that should be made in case the level of the anomaly, obtained through the application of Tables 1 to 3, does not reflect its severity.

Table 1 - Degradation levels for gaskets anomalies

Gaskets		
Degradation Level	**Anomalies description**	**% affected**
Level 0 **Very good**	No visible degradation	-
Level 1 **Good**	Accumulation of debris	> 20%
	Colour changes/superficial deterioration of the gasket [I/S] [A] [PVC]	≤ 10%
Level 2 **Slight degradation**	Colour changes/superficial deterioration of the gasket [I/S] [A] [PVC]	> 10% e ≤ 50%
	Deterioration of the coating of the putty seal [W]	> 10% e ≤ 20%
	Biological growth	≤ 15%
Level 3 **Moderate degradation**	Colour changes/superficial deterioration of the gasket [I/S] [A] [PVC]	> 50%
	Deterioration of the coating of the putty seal [W]	> 20% e ≤ 40%
	Biological growth	> 15% e ≤ 30%
	Detachment/discontinuity of sealing material *	> 10% e ≤ 30%
Level 4 **Severe degradation**	Deterioration of the coating of the putty seal [W]	> 40%
	Biological growth	> 30%
	Detachment/discontinuity of sealing material	> 30%
	Absence of sealing material	> 10%

Table 2 - Degradation levels for the material and coating of the framework

Material and coating of the framework		
Degradation Level	**Anomalies description**	**% affected**
Level 0 **Very good**	No visible degradation	-
Level 1 **Good**	Accumulation of debris	> 20%
	Coating colour change	≤ 10%
	Cracking/dotted coating	≤ 10%
	Detachment/absence of coating	≤ 10%
Level 2 **Slight degradation**	Coating colour change	> 10% e ≤ 50%
	Cracking/dotted coating	> 10% e ≤ 50%
	Detachment/absence of coating	> 10% e ≤ 50%
	Biological growth	≤ 15%
Level 3 **Moderate degradation**	Coating colour change	> 50%
	Cracking/dotted coating	> 50%
	Biological growth	> 15% e ≤ 30%
	Detachment/absence of coating	> 50%
	Corrosion of the framework material [I/S] [A] *****	> 10% e ≤ 20%
	Attack of xylophages [W] *****	≤ 10%
	Attack of rot fungi/mould [W] *****	≤ 10%
	Aging of the framework material [W] [PVC]	> 10% e ≤ 20%
	Deformation of the framework *	> 10% e ≤ 30%
	Open joints/gaps *	> 10% e ≤ 30%
Level 4 **Severe degradation**	Biological growth	> 30%
	Corrosion of the framework material [I/S] [A]	> 20%
	Attack of xylophages [W] *****	> 10%
	Attack of rot fungi/mould [W] *****	> 10%
	Aging of the framework material [W] [PVC]	> 20%
	Deformation of the framework *	> 30%
	Open joints/gaps *	> 30%

Table 3 - Degradation levels for metal fittings

Metal fittings		
Degradation Level	**Anomalies description**	**% affected**
Level 0 **Very good**	No visible degradation	-
Level 1 **Good**	Accumulation of debris	> 20%
Level 2 **Slight degradation**	Corrosion/degradation of mechanisms *	> 20% e ≤ 40%
	Damaged/absence of mechanisms *	> 20% e ≤ 40%
Level 4 **Severe degradation**	Corrosion/degradation of mechanisms *	> 40%
	Damaged/absence of mechanisms *	> 40%

[A] - Applicable to aluminium 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 or in operation problems of the frame, see Table 4.

Table 4 - Adjustment to be applied to the level of degradation of the anomaly, if it causes insufficient tightness or operability

	Performance deficit detected				
Description	Air tightness		Watertightness		Operability
	Minor intake of a high air flow	Major intake of a high air flow	Minor intake of a high water flow	Major intake of a high water flow	Inoperable window
Level of degradation	Level 2	Level 3	Level 3	Level 4	Level 4

5. Methodology

The model proposed in this study is based on the methodology presented by Gaspar (2009), considering the specific characteristics of window frames. The same criteria as Gaspar (2002), Silva *et al.* (2011) and Serralheiro *et al.* (2017) is thus adopted, where the end of the service life of the element under analysis is defined at degradation level 3, which means that window frames with a degradation level of 3 or above have reached the end of their service life.

5.1 Degradation indicator, Gaspar's (2009) model

Gaspar (2009) proposes a numerical index, which represents the value of the severity of degradation of a façade, normalized in relation to a reference façade area. For window frames, the severity of the normalized degradation is given in the following equation (1).

$$S_{w,c} = \frac{\sum(L_v \times k_n \times k_{a,n})}{L_{T,v} \times k_{max,v}} + \frac{\sum(L_c \times k_n \times k_{a,n})}{L_{T,c} \times k_{max,c}} + \frac{\sum(L_f \times k_n \times k_{a,n})}{L_{T,f} \times k_{max,f}} = \frac{E_{w,p}}{k_{max}} \quad (1)$$

Where:

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

L_v - dimension of gaskets affected by anomalies, in cm;

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

L_f - number of metal fittings affected by anomalies;

k_n - multiplication factor for *n* anomaly, 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;

$L_{T,v}$ - overall dimension of the gaskets, in cm;

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

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

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

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

$k_{max,f}$ - 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, gaskets, framework material and coating, and metal fittings anomalies);

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

Gaspar (2009) tested two scenarios: in the first one, used as benchmark, all anomalies have equal weight ($k_{a,n} = 1$); in the second, weighting coefficients were assigned according to the severity of the anomaly. With the second scenario, values closer to the observed reality were obtained, which means, values that reflected, in a more adequate way, the reality observed during the inspections carried out on the façades. The same process is applied in the current study, in which the values adopted for the weighting coefficients are presented in Table 5. They are defined by how they affect compliance with the minimum requirements of the element; its tendency to cause new anomalies or increase the propagation speed of existing ones;

and its repair cost, since this may also influence the service life of the element.

Table 5 - Weighting factors according to each type of anomalies

Gasket anomalies

Accumulation of debris	Colour changes/superficial deterioration of the gasket	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 colour 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/mould**	**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 [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 aluminium framework; **[I/S]** - Applicable to iron/steel framework; **[W]** - Applicable to wooden framework**; [PVC]** - Applicable to PVC framework

In Table 6, the correlation between the levels of degradation and the degradation severity is shown. Since the end of the service life of the window frames corresponds to level 3 of degradation, window frames with a severity of degradation exceeding 20% are considered to have reached the end of their service life. The correlation is based on the Gaspar's model (2009), with appropriate adaptation to the window frames.

Table 6 - Correlation between the degradation indicators

Degradation levels	$S_{w,c}$
Level 0	$S_{w,c} \leq 1\%$
Level 1	$1\% < S_{w,c} \leq 10\%$
Level 2	$10\% < S_{w,c} \leq 20\%$
Level 3	$20\% < S_{w,c} \leq 40\%$
Level 4	$S_{w,c} > 40\%$

By calculating the severity of degradation of the window frames inspected, the degradation evolution was plotted. In Figures 1 and 2, the plot of the degradation evolution for aluminium and wood frameworks, respectively, is presented.

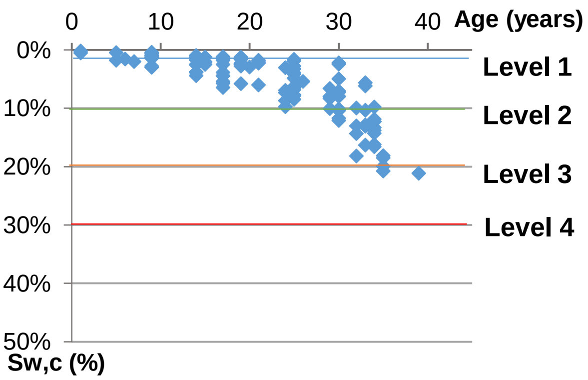

Figure 1 - Degradation severity of aluminium framework inspected during the fieldwork

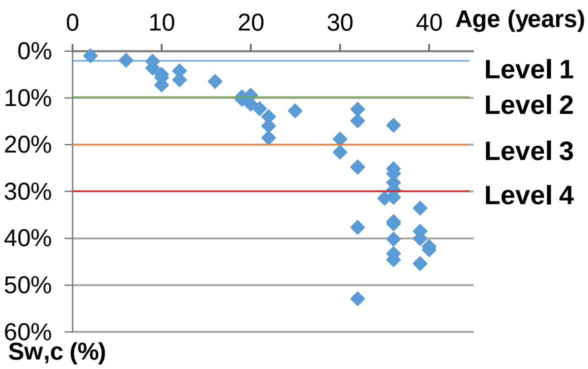

Figure 2 - Degradation severity of wooden framework inspected during the fieldwork

5.2 Degradation curves

The degradation curves show the loss of performance over time of the element analysed. In Figures 3 e 4, the degradation curves for the aluminium e wooden frameworks, respectively, analysed during the fieldwork is presented. In the case of PVC framework, the low amount of data collected more than 13 years old severely limits the study reliability of its degradation evolution.

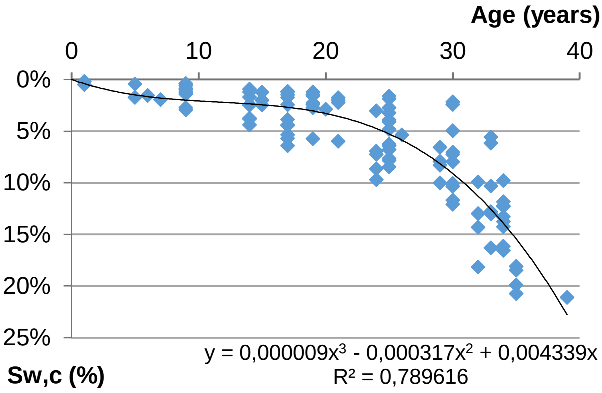

Figure 3 - Degradation curve of the 112 aluminium frameworks analysed in the fieldwork

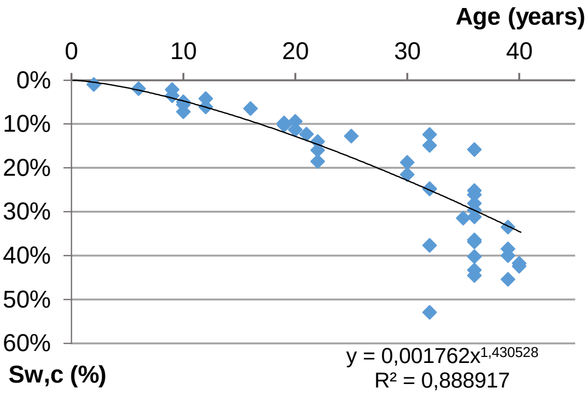

Figure 4 - Degradation curve of the 45 wooden frameworks analysed in the fieldwork

The degradation pattern obtained for aluminium framework is "S" shaped, reflecting an early stage where there is a noticeable loss of performance, 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 framework, the degradation curve has a convex shape, specifically a potential curve, this type of pattern 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.

In order to extend the knowledge of the influence of different factors on the degradation on window frames, various degradation curves are defined, according to the characteristics of the window frames analysed (Figures 5 to 12). However, due to the sample's size, some characteristics appear in few case studies, and thus the results obtained must be analysed with some caution, regarding their statistical significance.

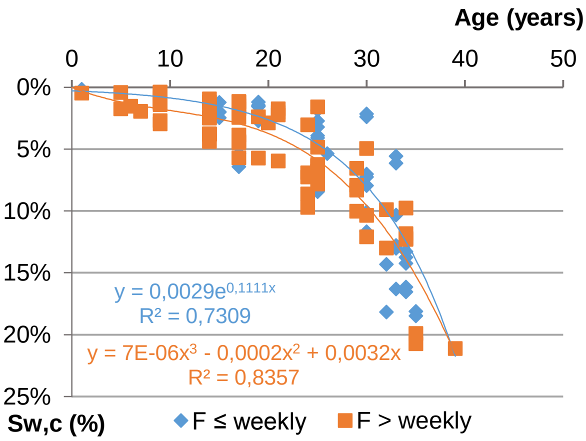

Figure 5 - Degradation curves of the aluminium framework, according to the frequency of cleaning actions

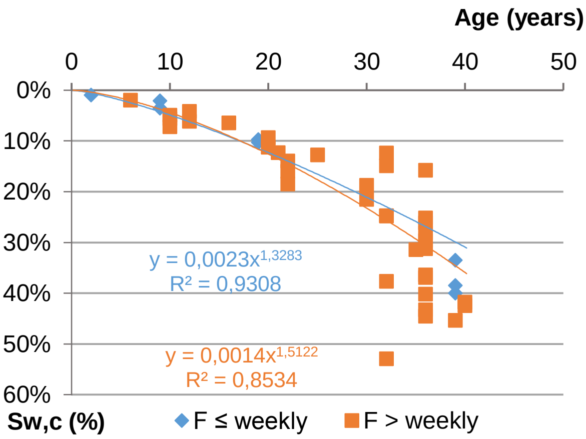

Figure 6 - Degradation curve of the wooden framework, according to the frequency of cleaning actions

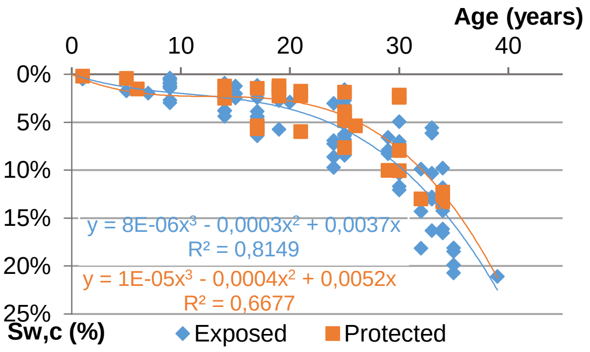

Figure 7 - Degradation curve of the aluminium framework, according the window span exposure

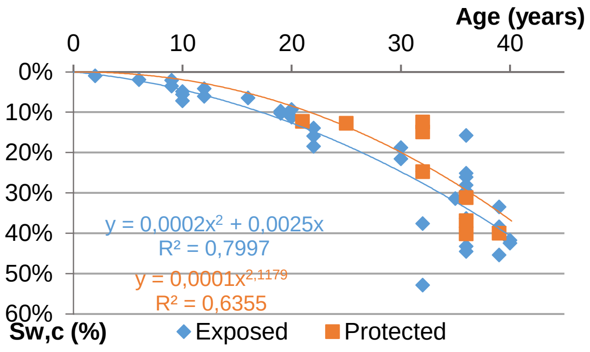

Figure 8 - Degradation curve of the wooden framework, according the window span exposure

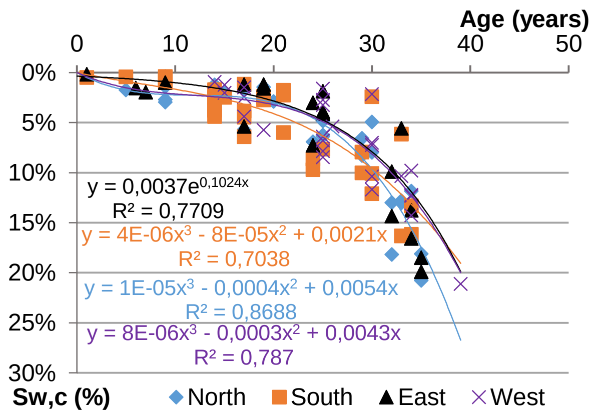

Figure 9 - Degradation curve of the aluminium framework, according to window span orientation

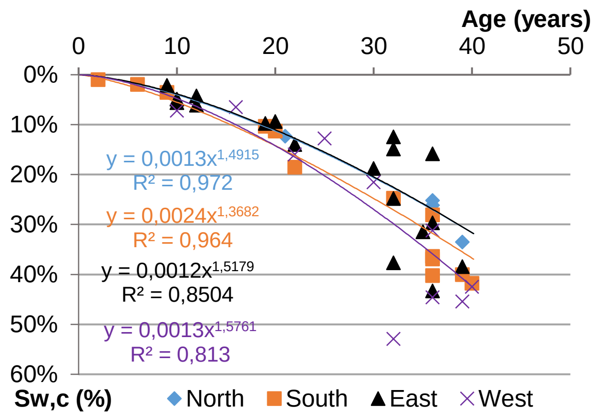

Figure 10 - Degradation curve of the wooden framework, according to window span orientation

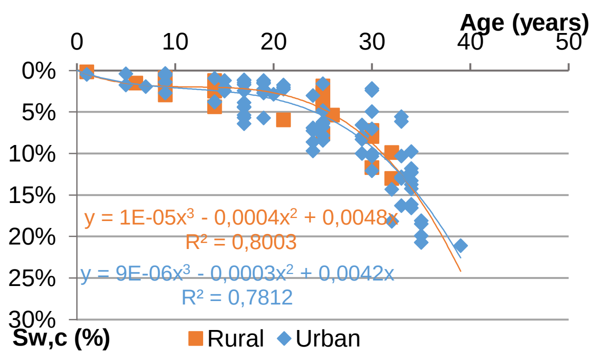

Figure 11 - Degradation curve of the aluminium framework, according to the surrounding environment

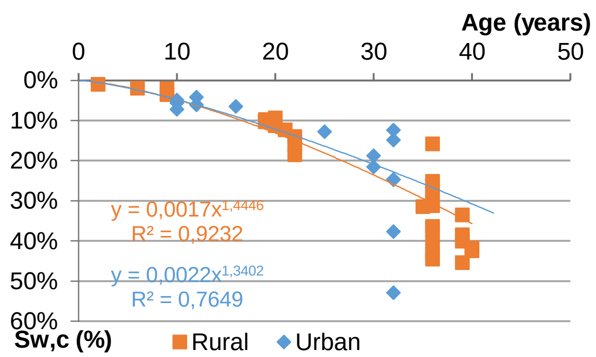

Figure 12 - Degradation curve of the wooden framework, according to the surrounding environment

6. Results and conclusions

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 development of degradation and service life prediction tools allows optimising the management of resources, thus reducing life cycle expenses. In this study, different degradation curves are proposed to describe the loss of performance of window frames over time and according to their characteristics. A determination coefficient of 0.79 is obtained, for aluminium frameworks, and of 0.89, for wooden framework, which shows a strong correlation between the curve and the observed severity of degradation of the window frames over time.

The expected service life (*ESL*) of window frames, according to their various characteristics, is shown in Table 7. The *ESL* obtained for aluminium frameworks is 37.6 years, which is in accordance with the results obtained by Cecconi *et al.* (2017), where the *ESL* values for this type of framework vary between 30 and 42 years, and with the HAMP (Housing Association Property Mutual Ltd.) manual, where the *ESL* for aluminium and wood frameworks is 35 years, when properly and regularly maintained. In the case of wooden frameworks, an *ESL* of 27.3 years is obtained, which is relatively lower than the value proposed in other works. This can be justified by the fact that the inspected window frames are not subject 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 higher 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 frameworks.

The results shown in Table 7 reveal that the most substantial difference in the *ESL* is the window span orientation, for both aluminium and wooden framework, with the aluminium frames being more negatively affected by the northern orientation and wooden frames by the southern and west orientation. In future research, it is essential to increase the sample size of PVC frames, especially for ages over 13 years, as well as, expanding the data regarding aluminium and wooden frameworks near the sea (< 5 km), enabling a more appropriate statistical analysis of these characteristics. The results obtained during this study can also be used for the development of the factor method applied to window frames, thus complementing and validating the model proposed.

Table 7 - Expected service life (ESL) of window frames

Framework material	Characteristic		*ESL* (years)	Change of *ESL* benchmark (%)	R^2
Aluminium	Benchmark service life		37.6	0	0.79
	Number of hours protected by shading devices (24 h)	< 10 h	36.9	-1.86	0.85
		≥ 10 h	38.0	1.06	0.75
	Frequency of cleaning actions	≤ Weekly	38.2	1.60	0.73
		> Weekly	38.1	1.33	0.84
	Window span exposure	Exposed	37.6	0	0.81
		Protected	38.4	2.13	0.67
	Orientation	North	36.2	-3.72	0.87
		South	39.7	5.59	0.70
		East	39.0	3.72	0.77
		West	39.0	3.72	0.79
	Surrounding environment	Rural	37.1	-1.33	0.80
		Urban	37.7	0.27	0.78
	Distance from the sea	< 5 km *	37.3	-0.80	0.57
		≥ 5 km	38.4	2.13	0.77
Wood	Benchmark service life		27.3	0	0.89
	Number of hours protected by shading devices (24 h)	< 10 h	26.1	-4.40	0.80
		≥ 10 h	28.3	3.66	0.76
	Frequency of cleaning actions	≤ Weekly	28.8	5.49	0.93
		> Weekly	27.2	-0.37	0.85
	Window span exposure	Exposed	26.3	-3.66	0.80
		Protected *	30.7	12.45	0.64
	Orientation	North *	29.4	7.65	0.97
		South	25.7	-5.86	0.96
		East	29.6	8.42	0.85
		West	24.8	-9.16	0.81
	Surrounding environment	Rural	26.8	-1.83	0.92
		Urban *	29.0	6.23	0.76
	Distance from the sea	< 5 km *	27.0	-1.10	0.54
		≥ 5 km	27.4	0.37	0.86

* The degradation curve associated with the characteristic does not have an acceptable number or distribution of data points or the correlation coefficient is lower than an admissible limit.

(orange)	Unfavourable characteristic in relation to the benchmark service life	(green)	Favourable characteristic in relation to the benchmark service life

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