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How Long Can a Wood Flooring System Last?

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Abstract: Wood is a natural, sustainable, and renewable material, which has been used as flooring for centuries, but not enough is known about its durability and performance over time when subjected to different degradation agents. This study proposes a methodology for the service life prediction of wood flooring systems, considering the impact of different factors that influence the floors' durability. For that purpose, a fieldwork survey is performed to evaluate the degradation phenomena of 96 indoor wood floorings in-use conditions, located in Portugal. The data collected are converted into degradation patterns that graphically illustrate the loss of performance of wood floorings over time. An estimated service life of 44 years is obtained. This study thus allows quantifying the impact of various characteristics on the indoor wood floorings' service life. The results reveal the high importance of the type of protection, the type of wood, and the type of floor (with a range of estimated service life values of around 18, 17 and 16 years, respectively). This study is a first step to understanding the degradation mechanisms of the wood flooring systems, in order to extend their service life, while allowing optimising of maintenance actions, thus promoting the durability and sustainability of these floorings.

Keywords: wood floorings; degradation phenomena; service life; durability

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1. Introduction

Nowadays, stakeholders are more aware of the relevance of healthy and sustainable buildings [1]. Recent studies [2] reveal that people in industrialized countries spend 90% of their time inside buildings and, therefore, the presence of natural elements, as wood floorings, can improve the users' physical and psychological well-being [3].

Wood has been used around the world, by different civilisations, for millennia [4], and it is one of the most common and attractive solutions for flooring worldwide. This widespread use is mainly due to the availability of this material, even in most inhabited regions of the world; however, not all wood species are appropriate for the various building uses [5]. Since wood is a natural material, its variable natural durability [6] makes it necessary to carefully evaluate its characteristics as a flooring to ensure that it is suitable for its intended use, presenting a durability compatible with the users' requirements and expectations. Therefore, when selecting a wood flooring system, users may ask "how long can a wood flooring system last?"

Romagnoli et al. [7] state that a major goal of wood technology research is still developing long-lasting wood elements with adequate mechanical performance, in other words, durable solutions. For that purpose, the wood-deteriorating agents and mechanisms that affect the wood flooring's long-term performance and service life should be identified [6]. Based on this knowledge, different degradation models can be established, considering the probable incidence of the degradation agents over time. Fundamentally, the degradation of wood elements occurs due to the presence of different degradation agents, which are usually divided into abiotic and biotic. The abiotic agents are related with weathering phenomenon, due to the exposure to damp, UV radiation, temperature, or other factors related to dynamic impacts, and abrasion and wear [8,9]. These factors are connected to physiological conditions for the presence of biotic degradation agents (e.g., subterranean insects and other xylophage insects). Both biotic and abiotic agents contribute to the deterioration of wood elements, in a complex and interconnected phenomenon [10], leading to the physical, chemical, mechanical, or biological alteration of the elements over time.

Why does knowing the service life of wood flooring systems matter? There are several important reasons for minding the wood floorings' service life. This knowledge allows adopting durability design procedures and adequate solutions at the design stage, selecting the most suitable wood type and protection for a specific use. Moreover, it allows optimising the maintenance strategies, in order to reduce the number of replacements (capitalising the investment in this flooring solution), while adopting correct measures for maintain the floors in acceptable conditions during their life cycle.

How can service life prediction be performed? The definition of reliable models for the durability and service life of wood floorings has not received as much consideration as for other materials [11]. Most of the existing studies assume an expected service life for wood floorings, but is this value credible? In reality, the actual service life of a given wood flooring depends on various factors including: (i) the quality of wood and the protection treatment; (ii) the typology and thickness of the wood elements (a parquet of solid wood can be more durable than a floor with only a few millimetres of noble wood); (iii) the conditions to which the flooring is exposed; and (iv) how well the flooring is maintained during use, besides subjective criteria. In practice, long-term data are not available, and the predictions are essentially based on manufacturers' data, accelerated testing, or extrapolations from the performance of similar materials [12]. Furthermore, current methods result from oversimplifications, and do not provide any information regarding the degradation mechanisms and the influence of critical factors that affect the performance of the wood floorings over time [13].

In this sense, in this study, a methodology for the service life prediction of indoor wood flooring is proposed, analysing in-service performance data, in order to acquire some knowledge related to the impact of the floors' characteristics in their expected service life. This research follows the methodology proposed by Gaspar and de Brito [14,15] for the service life prediction of buildings' envelope elements, which has been applied to several external façade claddings [16,17]. As a research hypothesis, it is considered that this general methodology for service life prediction of the elements of the building envelope can also be applied to predict the service life of wood flooring systems. Therefore, in this study, this methodology is applied, for the first time in the literature, to predict the service life of an element in the interior of the building. The methodology adopted is based on data collected by visual inspection, during a fieldwork survey, concerning the degradation condition of wood flooring systems. In this study, 34 Portuguese in-use houses have been inspected, corresponding to a total of 96 wood flooring systems. These data are analysed and converted into a numerical indicator, which portrays the overall degradation condition of the wood floorings analysed, which allows a graphical description of the loss of performance of these components over time and according to their characteristics. These analyses allow identifying an estimated service life of the wood flooring systems analysed, identifying the most relevant parameters for the degradation of these elements over their service life.

2. Materials and Methods

A fieldwork survey is used to collect all the relevant information for the classification of the anomalies present in the cases studies analysed, to define a model for predicting the service life of wood floorings. This survey is crucial for the definition of degradation curves, which allow evaluating the loss of performance of the wood flooring systems over time. For that purpose, 96 wood floorings, with different ages (i.e., at different stages of their service life) and various characteristics, were analysed, to obtain a degradation pattern of these floorings, through the comparison of the degradation condition of different examples. Some floors were analysed several years after installation, which makes it impossible to know in detail some constructive characteristics of the wood floors analysed, such as the thickness of the wood elements, the type of fastening to the support and the species of the wood, which can be impossible to obtain without a significant margin of error in several case studies.

The application of additional diagnosis techniques (e.g., application of laboratory tests to evaluate more specific characteristics of the wood species) may lead to more accurate results, but they are of little use in practice, both due to time constraints and additional costs for the analysis of the floors' degradation conditions. The existence of simple tools makes it possible to provide an estimation of the service life of wood flooring systems, which is certainly more relevant than making informed assumptions, due to the lack of technical or material capacity to apply more advanced or laboratory techniques for analysing wood floors. This study thus intends to provide an empirical tool, based on visual inspections, which is, in most situations, the technique used to assess the condition of the floors, assisting the decision to carry out maintenance actions, to provide some information regarding the degradation of the floors, their service life, and the factors that condition it.

The sample analysed is in Lisbon, Portugal, with construction periods between 1930 and 2018. The indoor wood floors analysed are subjected to regular maintenance, for example, either dry cleaning or wet cleaning, and, sometimes, the finishing layer is replaced. However, in the sample analysed, six case studies have been subjected to a generalised maintenance intervention (with the replacement of wood elements), and, in this scenario, it is assumed that this intervention restores the initial condition of the floor, which implies that the "age" of these floors correspond to the period between the last intervention and the inspection time.

The degradation condition of the indoor wood flooring systems is evaluated though in situ inspections, aided using a moisture-meter in singular cases of humidity problems, as anomalies caused by the presence of humidity do not necessarily imply the detection of high levels of humidity, at the time of inspection.

The anomalies observed in wood floorings can be considered a symbol of these degradation factors, which may be caused by natural or human actions, inadequate use, lack of maintenance, or unpredictable events (accidents or vandalism). Figure 1 shows some examples of the anomalies observed in the wood floorings analysed during the fieldwork survey.

In this study, the main anomalies that can occur in wood flooring systems are divided into three main groups [18,19]:

- Aesthetic anomalies, related to the visual or surface alteration of wooden floors, namely staining or colour change, cigarette marks, scratches or wrinkles, wear or detachment of the finishing layer, stains; anomalies due to inadequate maintenance, and wear of the wood material;
- Functional anomalies, which compromise the use of the flooring system (e.g., the presence of detached elements may jeopardize the users' safety) and can also affect the mechanical resistance and the performance of the wood flooring, namely, warping; swelling or other flatness deficiencies; either cracking of elements, joints, or both; broken or splintered elements; rot (identified either by changes in colour, texture in the finishing layer, or both); moisture stains; disaggregation; pulverulence; xylophage attack; and loss of wood elements; and
- Anomalies in joints, which are related to the deterioration of the filling material of the joints; the presence of these anomalies may promote the degradation of the wood flooring system. In this group, three anomalies are considered, namely, colour change of the filling material, detachment, or loss of the filling material of the joints and change of the joint size.

Different levels of degradation have been defined for each group of anomalies and, in some cases, for each specific anomaly. The degradation levels of each anomaly consider the type of anomaly and the number/size of its defects. Consequently, to distinguish the severity of the anomalies, percentages of their extent have been defined on the surfaces to be analysed. These percentages and the proposed degradation levels for each of the groups of anomalies are presented in Tables 1–3.

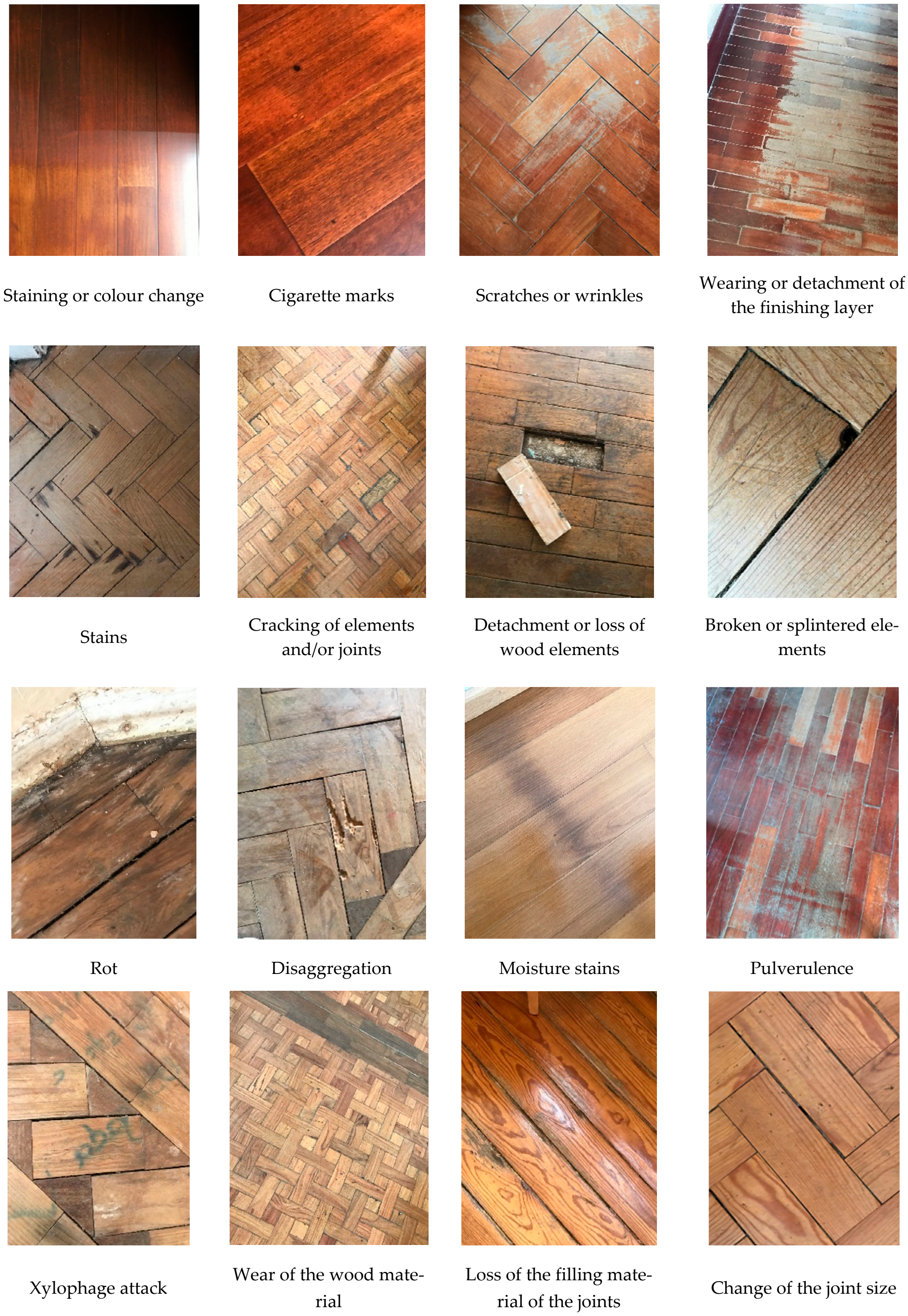


Figure 1. Illustrative examples of the anomalies observed in the wood floorings analysed.

Table 1. Degradation levels of aesthetic anomalies.

Anomalies	% Affected	Degradation Level (k_n)
Colour change	0–20	1
	20–60	2
	60–90	3
	90–100	4
Cigarette marks	0–20	3
	20–100	4
Scratches or wrinkles	0–20	1
	20–60	2
	60–90	3
	90–100	4
Wearing or detachment of the finishing layer	0–20	1
	20–60	2
	60–90	3
	90–100	4
Stains	0–10	1
	10–20	2
	20–60	3
	60–100	4
Anomalies due to inadequate maintenance	0–20	1
	20–60	2
	60–90	3
	90–100	4
Wear of wood material	0–10	1
	10–50	2
	50–90	3
	90–100	4

Table 2. Degradation level of joint anomalies.

Anomalies	% Affected	Degradation Level (k_n)
Colour change	0–20	1
	20–50	2
	50–90	3
	90–100	4
Detachment or loss of the filling material of the joints	0–20	1
	20–50	2
	50–90	3
	90–100	4
Change of joint size	0–20	1
	20–50	2
	50–90	3
	90–100	4

Table 3. Degradation levels of functional anomalies.

Anomalies	% Affected	Degradation Level (k_n)
Warping, swelling or other flatness deficiencies	0–10	1
	10–30	2
	30–90	3
	90–100	4
Cracking of elements and/or joints	0–10	1
	10–40	2
	40–90	3
	90–100	4
Broken or splintered elements	0–5	1
	5–10	2
	10–50	3
	50–100	4
Rot	0–5	1
	5–10	2
	10–50	3
	50–100	4
Moisture stains	0–5	1
	5–20	2
	20–50	3
	50–100	4
Disaggregation	0–10	1
	10–40	2
	40–90	3
	90–100	4
Pulverulence	0–10	1
	10–30	2
	30–90	3
	90–100	4
Xylophage attack	0–30	3
	30–100	4
Loss of wood elements	0–5	2
	5–20	3
	20–100	4

In this study, only the anomalies arising from use and due to the natural degradation process are considered, thus not contemplating major design or constructive errors (e.g., the presence of sapwood is considered a design characteristic and not an anomaly, in other words, it may be considered as a defect, but it is certainly a constructive defect), nor discrete events (such as vandalism actions). These phenomena are not considered, as they do not represent the natural evolution of the degradation of wood floors over time and are therefore not liable to be mathematically modelled.

These percentages were defined based on experts' opinions, considering the pathological context of the wood floors analysed, also taking into account and calibrating the degradation scale initially proposed by Prieto and Silva [18] for wooden façades. Each anomaly is rated on a discrete scale from 0 to 4, according to the following definitions: level 0 corresponds to a floor with no visible degradation; level 1 to the presence of visible anomalies, even though the floor remains in a good overall condition; level 2 to a floor that shows slight degradation signs; level 3 to a floor that shows moderate degradation; and level 4 to a floor that presents generalized degradation.

In this study, the service life prediction method initially proposed by Gaspar and de Brito [14,15] is adopted. This methodology is a deterministic empirical method, which intends to evaluate the loss of performance (or the evolution of degradation over time) of wood floorings in real service conditions and in different phases of their service life. The inclusion of the value of the areas affected by each type of anomaly in the proposed model allows assessing the extent of degradation and in parallel proceeding to the respective weighting in relation to the level of severity of each one. In this empirical method, the qualitative levels of degradation presented in Tables 1–3 are converted into quantitative information, in other words, a numerical index that establishes the overall degradation condition of the flooring, called severity of degradation (S_w). This numerical index is given by the ratio of the weighted degraded area to a reference area, equivalent to the whole flooring with the highest possible degradation level—Equation (1).

$$S_{w,wf} = \left(\sum(A_e \cdot k_n \cdot k_{a,n}) + \sum(A_f \cdot k_n \cdot k_{a,n}) + \sum(A_j \cdot k_n \cdot k_{a,n})\right) / \left(A \cdot \sum(k_{max})\right) \quad (1)$$

The parameters that are taken into account in the equation that is associated with the model used are: $S_{w,wf}$—severity of degradation of the wood floorings, in %; A—flooring area (m^2); A_e—area affected by aesthetic anomalies (m^2); A_f—area affected by functional anomalies (m^2); A_j—area affected by joint anomalies (m^2); 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; $\sum(k_{max})$—sum of the weighing constants, corresponding to the highest possible level of degradation (4 + 4 + 4).

Therefore, after collecting fieldwork information on the degradation condition of the various wood floorings analysed, their service life is predicted using a graphical and statistical analysis of the evolution of their severity of degradation index over time.

To estimate the severity of degradation index, the weighting coefficients presented in Tables 4–6 are used. These coefficients allow obtaining values closer to reality, in other words, values that reflect, in a more adequate way, the reality observed during the inspections carried out on the floorings. The weighting coefficients are defined considering the repair costs of each anomaly, as well as the propensity of the anomaly to cause new anomalies or increase the propagation rate of the existing ones, and the effects of the anomaly in decreasing the capacity of the flooring to fulfil the minimum performance requirements.

Table 4. Weighting factors associated to functional anomalies.

Anomalies	Weighting Factor ($k_{a,n}$)
Warping, swelling, or other flatness deficiencies	1.2
Cracking of elements, joints, or both	1.2
Broken or splintered elements	1.2
Rot	1.2
Moisture	1.2
Disaggregation	1.2
Pulverulence	1.2
Xylophage attack	1.2
Crumbling	1.2

Table 5. Weighting factors associated to aesthetics anomalies.

Anomalies	Weighting Factor ($k_{a,n}$)
Colour change	0.6
Cigarette marks	0.6
Scratches or wrinkles	0.6
Wearing or detachment of the finishing layer	0.6
Stains	0.6
Improper maintenance	0.6
Wear	0.6

Table 6. Weighting factors associated to joint anomalies.

Anomalies	Weighting Factor ($k_{a,n}$)
Colour change	0.6
Detachment or loss of the filling material of the joints	1
Change of joint size	1

3. Results and Discussion

3.1. Definition of a Degradation Curve for Wood Flooring Systems

In this study, and through the adoption of the proposed model, the evolution of the degradation condition of wood floorings over time can be characterised by a degradation curve. This curve (Figure 2) is a graphical representation of the evolution of the degradation condition of wood floorings over time, and is obtained through a regression analysis between the numerical index that expresses the degradation of wood floorings ($S_{w,wf}$) and their age, considering the sample analysed in the fieldwork survey. The regression model is used to evaluate the variability of y (i.e., the severity of degradation index) that varies with the variability of x (i.e., the age of the wood floors) [16], or in other words, the regression analysis allows identifying the percentage of the variability of the severity of degradation of wood floors that are explained by their age.

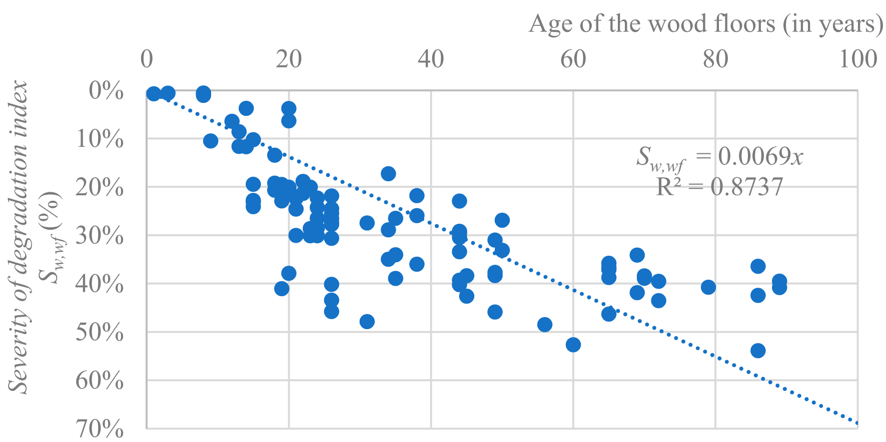


Figure 2. Regression analysis between the numerical index that expresses the degradation of the 96 wood flooring systems ($S_{w,wf}$) and their age.

In this study, a linear degradation pattern is adopted to describe the degradation of the sample analysed (97 wood floorings). According to various authors [20–23], a linear degradation pattern is adequate and valid to describe the degradation of interior components, in standard service conditions. This pattern describes a time-dependent linear degradation of wood floorings, which are subjected to consistent and continuous degradation agents over their service life, especially, when the floorings' users are the same throughout their lifetime, adopting consistent conditions of use and maintenance. Moreover, the climatic degradation agents (e.g., UV radiation, humidity, and temperature) acting on the interior floors are less aggressive and less variable (e.g., interior floors are not subjected to rainfall and direct solar radiation, whose intensity varies over the year, as well as during the day) than the agents acting on the external claddings [24].

The estimated service life of the wood flooring systems can thus be determined based on this overall degradation curve, through the intersection between the degradation curve and the theoretical limit adopted to establish the end of service life of this component. As mentioned in various studies [16,25], the end of service life is a conventional limit that it is not easy to specify, which relies on subjective criteria as the users demands and expectations, the funds available for maintenance actions, among other parameters, are difficult to model.

Figure 3 shows different examples of three levels of severity of degradation of wood floorings, revealing that a flooring with a severity of degradation of 20% still presents an adequate condition level, and therefore, adopting a maximum severity of degradation of 20% seems excessively conservative to establish the end of service life of wood flooring systems. Conversely, a floor with a severity of degradation of 40% already shows clear signs of generalised deterioration, and the presence of some anomalies that compromise the floors' functionality. In this sense, a limit of 40% for the severity of degradation, to establish the end of service life, seems too high and inadequate to fulfil the users' demands. Therefore, in this study, it is assumed that a severity of degradation of 30% corresponds to the end of service life of a wood flooring.

$S_{w,wf}$ = 20% $S_{w,wf}$ = 30% $S_{w,wf}$ = 40%

Figure 3. Illustrative examples of the overall condition of the wood floorings for different levels of the severity of degradation index.

Having established this limit, the estimated service life of the wood flooring systems can be obtained graphically; for the sample analysed and based on the overall degradation curve defined in Figure 2, an estimated service life of 44 years is obtained, which is in accordance with the literature and empirical knowledge about the durability of these elements. According to the existing literature on the durability of wood flooring systems, the service life of these floors can vary significantly. Nebel et al. [26] obtained an estimated service life of 10 years for multilayer parquet, while Seiders et al. [27] state that a floor can last up to 100 years, with a service life similar to the building's. Anderson et al. [28] obtained an estimated service life of 20 years for multilayer parquet glued to the substrate. Nebel et al. [26], for 8 mm parquet and 10 mm parquet, obtained an estimated service life of 25 years. Jönsson et al. [29] and Jönsson [30] estimated a service life of 40 years for pine flooring. Scharai-Rad and Welling [31] and Petersen and Solberg [32] suggested a service life of 45 years for oak flooring, while Eaton and Hale [33] and Asdrubali et al. [34] state that oak woods present an estimated service life ranging between 35 and 50 years. Adalberth [35] and Mithraratne and Vale [36] obtained an estimated service life of 50 years, for 22 mm parquet. Gunther and Langowski [37] obtained an estimated service life of more than 50 years for parquet. Aktas and Bilec [38] concluded, with an 80% confidence interval, that the service life of a wooden housing floor is, on average, 40 years. This confidence interval was defined in accordance with ISO 15686-1 [39], to define minimum and maximum limits for the variance of the results of the estimated service life, with a minimum of 15 years and a maximum of 73 years.

3.2. Influence of the Characteristics of Wood Flooring Systems on Their Service Life

The dispersion of values proposed in the literature for the expected service life of wood flooring systems reveals that the wide range of characteristics of wood floorings strongly influences their behaviour over time, affecting their durability. Reinprecht [40] refers that the service life of wood elements depends essentially on the natural durability of the wood, but also varies considerably according to the design characteristics, the protection applied, and the exposure and maintenance conditions. In this sense, the evolution of the degradation condition of wood floorings should also be analysed as a function of the different characteristics of these floors.

In this study, different curves are proposed according to the relevant characteristics of the wood floorings analysed. The type of wood is the first characteristic analysed, and five categories are considered to typify the sample analysed: (i) oak; (ii) eucalyptus; (iii) mahogany; (iv) pine; and (v) tropical woods (e.g., *Couratari oblongifolia*, *Dipteryx odorata* and *Diplotropis* sp.). In the sample analysed (Figure 4), oak and eucalyptus wood floorings present the lower estimated service lives, around 33 years, followed by mahogany floors, with an estimated service life of 35 years, and by tropical woods, with an estimated service life of 43 years, and, finally, by pine wood floorings, with an estimated service life of 50 years.

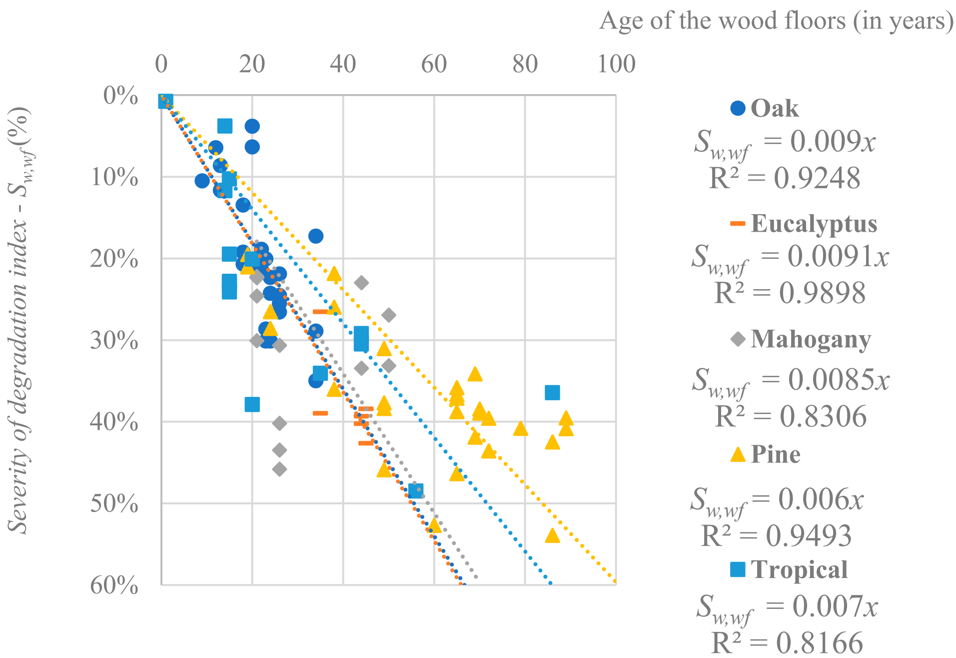


Figure 4. Regression analysis between the numerical index that expresses the degradation of the 96 wood flooring systems ($S_{w,wf}$) and their age, according to the type of wood.

Various studies [41,42] emphasise the crucial role of the natural durability of the wood species on the service life of a wood flooring. The results obtained may seem incongruous with the empirical perception regarding the durability of wood species. Usually, pine is considered as a less durable type of wood and non-resistant to decay due to xylophage attack [43,44]. However, as a natural material, the physical properties of a wood element vary significantly, even within the same wood species [45]. Cruz et al. [46] refer that, usually, the wood species are divided into softwood (e.g., pine) and hardwood (e.g., oak, eucalyptus, and some tropical species) and among hardwood species, the properties of wood range between not very resistant nor durable to very resistant and durable woods (as some Brazilian species, as the ones included in the category "tropical" analysed in the present study).

Therefore, the results reveal three major conclusions (the sample analysed is relatively small, so the results should be analysed with some caution): (i) oak, eucalyptus and mahogany species present similar degradation curves, revealing lower estimated service lives than tropical or pine wood floorings; (ii) tropical floors are usually more durable, since more naturally durable wood species have been applied while greater care was taken at the time of execution given the specificity of the material, and greater attention is taken in the floors' maintenance; and, (iii) the main reason why pine floors are more durable, within the sample analysed, is because 75% of the pine floors inspected are traditional tiles, which have a significant thickness, and whose maintenance implies polishing and applying wax, as a protective layer, weekly or monthly, thus mitigating anomalies that may occur over the service life of the floor.

In this sense, while the quality of the wood used is undoubtedly relevant to the service life of wood flooring systems, correct design also plays an important role [34]. In the sample analysed, three types of floor solutions are analysed [47–49]: (i) parquet, consisting of a set of wooden slats, with a total thickness around 8 mm; (ii) traditional floorboard, entailing several wooden strips that can be solid or laminated, with a thickness between 18 and 20 mm; and (iii) traditional tiles of solid wood, with a thickness between 17 and 22 mm. The degradation curve obtained according to the type of floor (Figure 5) reveal that parquet floors are the less durable of the sample analysed, with an estimated service life of 33 years, followed by traditional floorboard, with an estimated service life of 37 years, and by traditional tiles, with an estimated service life of 49 years. The thickness of the wood elements seems to play an important role in the durability of the wood floorings; naturally, thicker floorings, have longer estimated service lives, in addition to allowing more intrusive maintenance actions, which allow extending the service life of the elements in more adequate conditions of use.

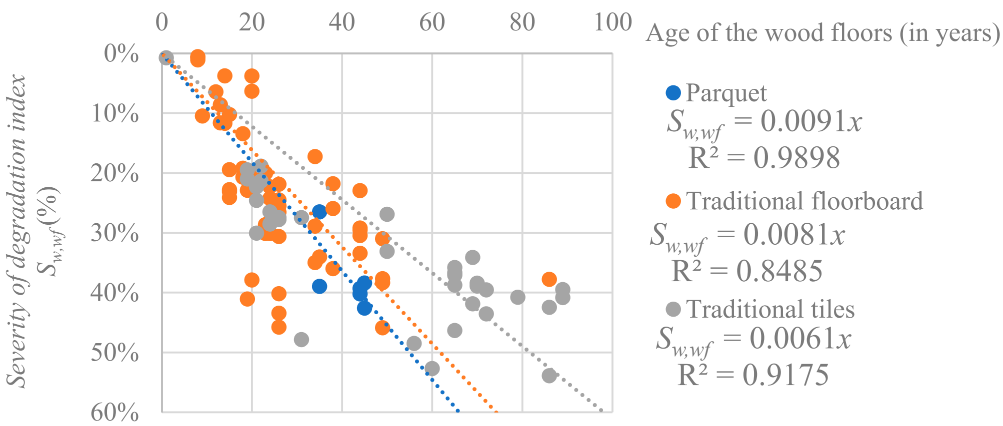


Figure 5. Regression analysis between the numerical index that expresses the degradation of the 96 wood flooring systems ($S_{w,wf}$) and their age, according to the type of flooring system.

Other intrinsic characteristics of wood may also be analysed, as its hardness, which is a relevant property for the selection of a given wood used in flooring indoors [50,51]. The hardness of the wood elements is intrinsically related with their density, which depends on several factors, such as the tree species and growing conditions, which are variable in the same species and in the same tree [3]. In this sense, the sample analysed was divided into two categories: (i) softwood species, which usually present lower densities [3]; and (ii) hardwoods, usually more resistant to impacts, scratches, and wear [52,53]. Due to the multiplicity of characteristics that influence the hardness and density of a wood species, it is not possible to draw unequivocal conclusions regarding the impact of this characteristic in the service life of wood flooring, but Figure 6 presents some statistical analysis regarding the influence of the wood's hardness in the presence of related anomalies, revealing that hardwood floorings are less prone to suffer scratches, wrinkles, and wear of the wood material.

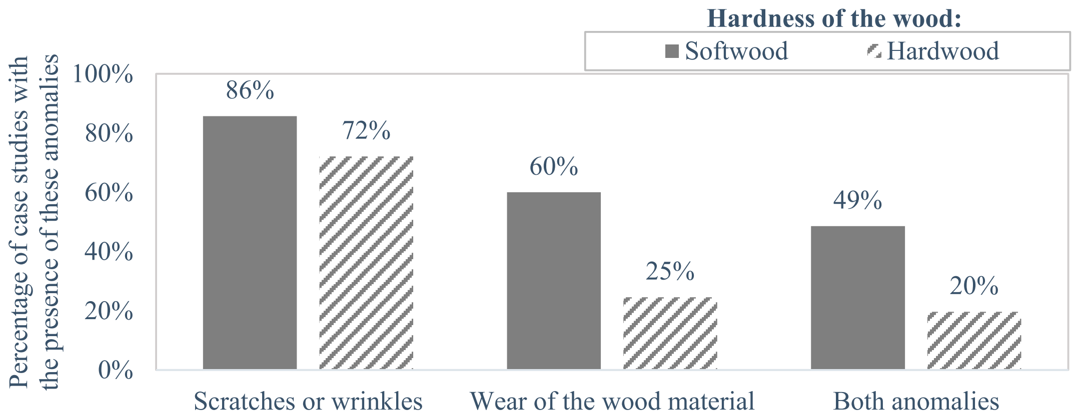


Figure 6. Statistical analysis of the presence of scratches or wrinkles and wear of the wood material, according to the hardness of the wood.

The type of surface coating of the wood floorings is also a relevant parameter to protect the floors from liquid water and direct UV radiation, avoiding anomalies that compromise the natural and aesthetic characteristics of the wood floorings, while increasing the service life of these floors [54]. Concerning the type of coating of the wood floorings, three types of protection treatments are analysed: (i) oil-based matte finishes; (ii) wax; and (iii) varnish. Figure 7 shows the degradation curves obtained for the sample under analysis, according to the surface coating. The sample corresponding to the oil-based matte finishes is small (7 case studies) and the older case study has 26 years, and therefore, no unequivocal conclusions can be drawn regarding the influence of this coating on the service life of wood floorings. The varnish coatings present a lower estimated service life (around 38 years), when compared with wood floorings with a wax coating (with an estimated service life around 52 years).

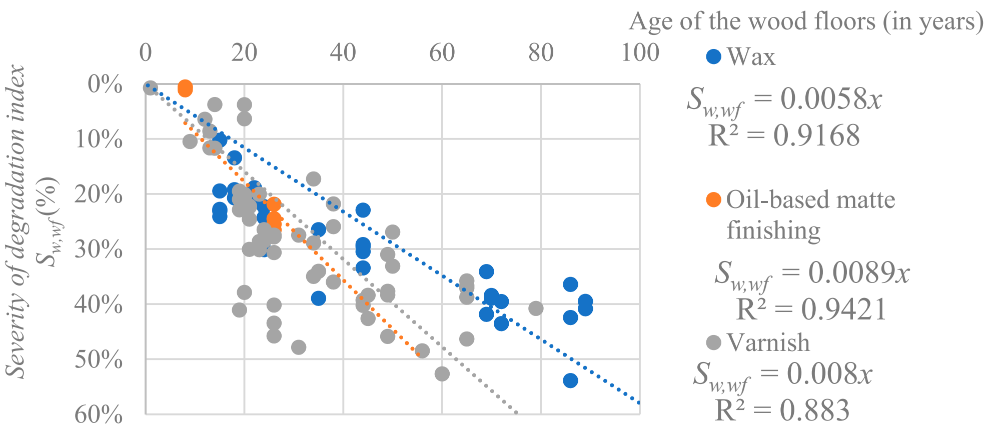


Figure 7. Regression analysis between the numerical index that expresses the degradation of the 96 wood flooring systems ($S_{w,wf}$) and their age, according to the surface coating.

Richardson [55] states that varnish can be an attractive solution to protect wood applied in interiors, but almost all varnishes suffer from a preferential wetting failure due to the fact that varnish is hydrophobic, and wood is hydrophilic, and in the presence of water, the interaction between the two materials may privilege the deterioration of the wood elements. Moreover, when exposed to the direct incidence of UV radiation, varnishes tend to oxidize and become opaque. Specifically, varnish degrades over time, and its efficiency is limited in time, losing elasticity, and becoming brittle, thus making the wood susceptible to various agents of deterioration. Unlike varnish, which is usually applied as a protective film, wax is usually impregnated in the wood [56], with generally longer periods of action, increasing the dimensional stability of the wood floorings exposed to moisture [57], and promoting a more homogeneous and regular degradation of the wood floorings over time. Furthermore, in Portugal, wood floorings with wax coatings tend to be maintained more regularly, with the removal of old wax and application of a new layer of wax.

The installation of wood floorings in contact with moisture or near moisture sources is seen as a risk factor that promotes the deterioration of these flooring systems [19,58]. Various studies [18,59,60] identify the presence of moisture as one of the main causes of anomalies in wood used as coating material. Figure 8 presents the degradation curve of wood floorings according to the exposure to moisture sources (e.g., sanitary facilities, kitchens). In the sample analysed, a wood flooring near to moisture sources has a 70% probability of presenting some anomaly related to the presence of water (e.g., moisture stains, rot, cracking). The results obtained confirm the that a wood flooring near or exposed to moisture sources reaches the end of its service life sooner (after 38 years) than a flooring protected from moisture sources, which only reaches the end of its service life after 45 years.

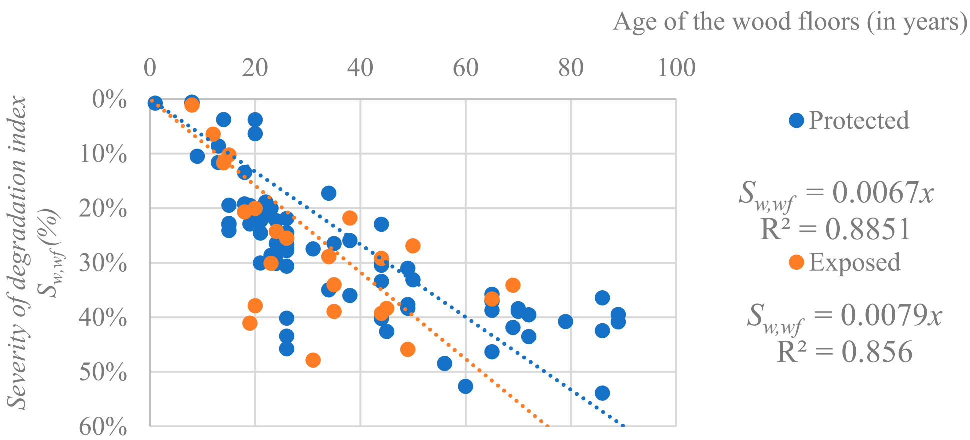
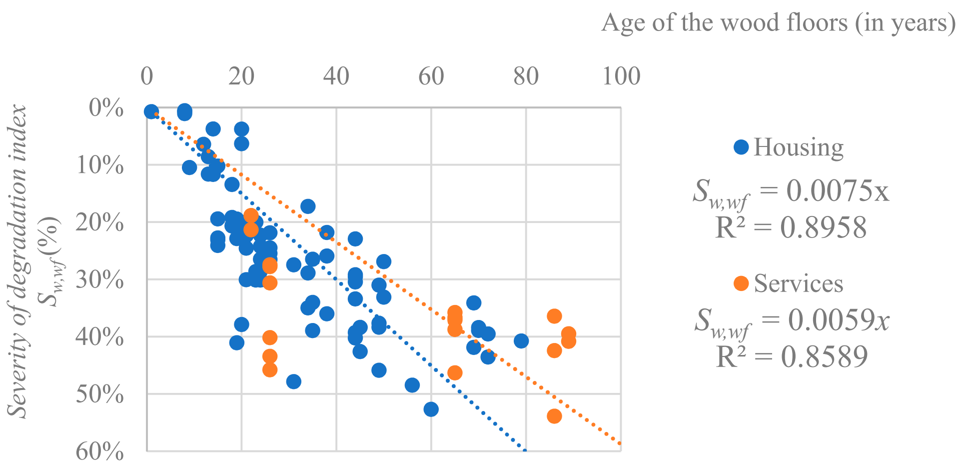
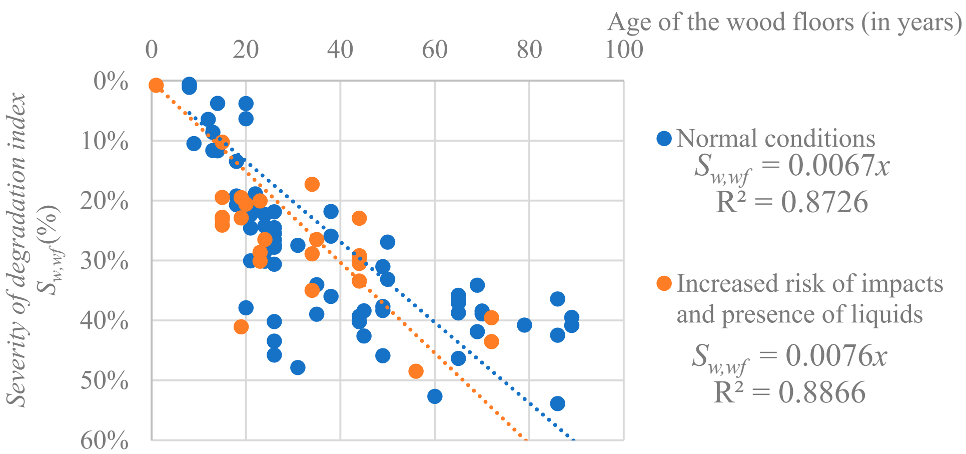


Figure 8. Regression analysis between the numerical index that expresses the degradation of the 96 wood flooring systems ($S_{w,wf}$) and their age, according to the exposure to moisture sources.

The degradation of wood floorings also occurs due to the action of mechanical or some chemical actions [46]. In the sample analysed, the case studies are not subjected to chemical degradation agents and, therefore, this degradation mechanism is not considered. On the other hand, the use conditions influence the degradation of the wood floorings analysed. Figure 9 shows two degradation curves according to the type of use and to the in-use conditions. First, the analysis of the type of use reveals that wood floorings in services buildings present a higher estimated service life (around 51 years) than floors in housing (with an estimated service life around 40 years). This result reveals that, even though the floorings in services buildings are more exposed to an intense circulation and use, a more frequent and careful maintenance increases their estimated service life.



(**a**)



(**b**)

Figure 9. Regression analysis between the numerical index that expresses the degradation of the 96 wood flooring systems ($S_{w,wf}$) and their age, according to the type of use (**a**) and in-use conditions (**b**).

Moreover, in housing, some case studies are exposed to the presence of pets, children and some are used to have meals, which increases the risk of impacts and presence of liquids. When this risk is analysed, as in Figure 9b, an increased risk of impacts and presence of liquids leads to a lower estimated service life (around 39 years) than floors in normal in-use conditions (with an estimated service life of 45 years). A more detailed analysis is performed, evaluating the differences in the expected service life of wood floorings according to the house room, and although these values should be analysed with caution, given the small sample size, the following conclusions can be drawn: (i) dining rooms present the lowest estimated service life, around 28 years; (ii) followed by entrance halls, in which the circulation is more intense, with an estimated service life of 38 years; (iii) in third place come bedrooms, with an estimated service life around 42 years; (iv) classrooms and living rooms present estimated service lives of 46 and 47 years, respectively; and (v) finally, offices present an estimated service life of 49 years.

These results reveal two conflicting phenomena: on the one hand, floorings with more intense circulation should have lower estimated lives and this occurs in the case of halls. However, in the case of public buildings, offices and even classrooms, although circulation is more intense, maintenance is also more thorough and frequent, which counteracts with the higher rate of degradation of spaces. In other words, maintenance helps to preserve floors in adequate conditions for a longer time, while in residential buildings maintenance actions tend to be postponed, sometimes due to economic reasons.

Various studies [61,62] reveal the relevance of maintenance to mitigate the degradation of wood flooring systems and the impact of these actions to extend the floor's service life. In the sample analysed, the frequency of maintenance actions is divided into three categories, according to the information collected during the fieldwork survey, leading to the following results: (i) dry and wet cleaning, performed weekly, with an estimated service life of 44 years; (ii) dry cleaning, performed weekly, and wet cleaning performed monthly, with an estimated service life of 43 years; and (iii) dry and wet cleaning, performed monthly, with an estimated service life of 43 years. The differences obtained are insignificant, since all the case studies are frequently subjected to maintenance actions and, therefore, the impact of having regular maintenance cannot be fully evaluated. The type of maintenance varies between floorings, being more or less strict depending on the users; however, the actions carried out are not evaluated in detail (e.g., the cleaning products applied), thus not allowing assessing of the differences between the types of maintenance carried out in the different floorings analysed. The impact of the maintenance it is therefore more perceptible when other characteristics of the floorings are analysed, such as the surface protection or conditions of use, where the type of maintenance has an indirect impact on the floorings' service life according to these characteristics.

4. Conclusions

This study proposes an empirical degradation model to evaluate the on-site performance of wood flooring systems, considering a sample of 96 case studies. The evolution of the degradation condition of the sample analysed is discussed as a function of the different characteristics of these floors, and an estimated service was obtained for each one of the characteristics analysed. Table 7 presents a summary of the results obtained for the various characteristics of the wood floorings analysed. The sample analysed is small, from a statistical point of view; nevertheless, some statistically significant values were obtained. In this sense, a deeper statistical analysis (e.g., a multiparametric statistical analysis) would lead to debatable results, as the sample size could lead to the bias of the conclusions obtained. In future studies, with the improvement of the sample, it will be possible to carry out multiple regression analyses, which made it possible to consider the simultaneous effect of several variables on the degradation of wood floors.

The results obtained revealed, as expected, that the wide range of characteristics of wood floorings strongly influence their behaviour over time, affecting their durability. In the sample analysed, serious errors of construction or use are not considered. Additionally, when severe situations of degradation occur, the users usually perform maintenance and repair actions, in order to mitigate the progression of the degradation of the wood floorings, and, in some cases, restore their initial performance. In the sample analysed, all floorings are regularly maintained, which explains why this parameter, when grouped into the three categories considered, which already include a high maintenance periodicity, does not lead to significant differences in the overall service life of the wood floorings.

Moreover, the type of maintenance performed, as well as the cleaning products applied, are difficult to assess and can affect the state of degradation of the wood floorings. These conditions of maintenance are indirectly reflected on the use conditions. The type of use shows a variation in the estimated service life of 11 years, between floorings in public spaces and floorings in housing. The in-use conditions seem to be less relevant, with a lower impact on the overall estimated service life, with a small variation in the estimated service life (*ESL*) obtained for floorings exposed to high risks of impact and presence of liquids and floorings in normal conditions of use. The level of the users' demands associated with the sample analysed can also explain this result, since users that are more careful tend to lighten the relevance of this parameter.

The presence of moisture leads to a variation in the estimated service life of wood floorings of seven years, revealing that the proximity of a moisture source increases the incidence of anomalies related with this degradation agent, thus reducing the service life of these floorings.

Table 7. Summary of the estimated service life obtained according to the different wood floorings' characteristics.

	Characteristics	Estimated service life - *ESL* (years)	Determination coefficient (R^2)	Size of the sample	Impact on the overall ESL (years)
	Overall sample	*44*	*0.874*	*96*	-
Type of wood	Oak	33	0.925	26	↓ −11
	Eucalyptus	33	0.99	6	↓ −11
	Mahogany	35	0.831	13	↓ −9
	Tropical woods	43	0.817	23	↓ −1
	Pine	50	0.949	28	↑ 6
Type of floor	*Parquet*	33	0.99	6	↓ −11
	Traditional floorboard	37	0.849	56	↓ −7
	Traditional tiles	49	0.918	35	↑ 5
Type of finishing	Oil-based matte finishing	34	0.942	7	↓ −10
	Varnish	38	0.883	60	↓ −6
	Wax	52	0.917	30	↑↑ 8
Exposure to a moisture source	Exposed	38	0.856	24	↓ −6
	Protected	45	0.885	73	↑ 1
Type of use	Housing	40	0.896	79	↓ −4
	Public services	51	0.859	18	↑ 7
In-use conditions	Increased risk of impacts and presence of liquids	39	0.887	26	↓ −5
	Normal conditions	45	0.873	70	↑ 1
Maintenance	Dry and wet cleaning performed monthly	43	0.921	25	↓ −1
	Dry cleaning performed weekly, and wet cleaning performed monthly	43	0.963	9	↓ −1
	Dry and wet cleaning performed weekly	44	0.831	62	→ 0

Regarding the type of protection or finishing, the type of wood, and the type of flooring, these characteristics show a very significant impact on the estimated service life, in other words, a variation of 18, 17, and 16 years, respectively, is obtained for these characteristics. Therefore, these characteristics significantly influence the durability and service life of wood floorings, considering the high variation obtained for the estimated service life as a function of these characteristics, taking into account that the estimated service life of the overall sample is 44 years. This result confirms the influence of the susceptibility of wood to degradation mechanisms and the impact of design in the estimated service life of wood flooring systems.

The results obtained in this study allow quantifying of the variability introduced by the different characteristics of the wood floorings on their estimated service life, leading to an estimation in years, which is the first step to adopt more sustainable solutions during the design stage, adopting preventive measures and selecting adequate solutions for an intended use. By understanding the degradation mechanisms of the wood floorings and based on the results obtained in this study, the durability of wood floorings can be increased through the adoption of regular inspections and maintenance actions, thus promoting the sustainability of the solution and reducing its environmental impacts.

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writing—original draft preparation, P.C. and A.S.; writing—review and editing, J.d.B. All authors have read and agreed to the published version of the manuscript.

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