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# Damage Assessment of Pine Wood Facades in the First Years of Service for Sustainable Maintenance

**Joana Oliveira Almeida [1,2,*], Pedro Delgado [1,2], António Labrincha [1], Helena Parauta [1] and Bruno Lima [3]**

1 proMetheus, Instituto Politécnico de Viana do Castelo, 4900-347 Viana do Castelo, Portugal
2 CONSTRUCT-LESE, Faculty of Engineering (FEUP), University of Porto, 4200-465 Porto, Portugal
3 Hotel FeelViana, 4935-159 Viana do Castelo, Portugal
* Correspondence: joliveira@estg.ipvc.pt

**Abstract:** The importance of the sustainability of wood buildings is increasing. The renewed attention highlights the need to assess the wood deterioration accurately, in the initial years of service, to optimize treatment during its lifetime and reduce maintenance costs. This study presents a methodology for inspecting and classifying damage of wood in service, relying on visual inspection and oriented to non-structural wooden components. This approach enables more affordable, widespread, and frequent monitoring of wooden elements in use, promoting their routine maintenance. The methodology was tested in the pine wood (*Pinus sylvestris*) facades with up to 5 years of service in a hotel building in northern Portugal. Despite its relatively brief period of operation, the building displays indications of both abiotic and biotic degradation of the wood across all its different facade orientations. Based on that, the study highlights the natural aging of Scots pine according to the building's age, orientation, maintenance treatments, and exposure conditions. These findings provide insights into conservation plan optimization and emphasize the need for regular maintenance of wooden elements in outdoor environments, even in the early years of service.

**Keywords:** wood facades; *Pinus sylvestris*; aging evaluation; inspection; damage classification; maintenance plans



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## 1. Introduction

Extending the durability of timber, on the one hand, and preserving it in good condition, on the other, are very effective methods of saving money and energy, contributing to a higher sustainability of wooden constructions [1–4], whose future existence will increase, precisely as a result of environmental concerns.

The study of wood durability can be done based on its observation in real situations over a lengthy period or in an accelerated way in the laboratory. The accelerated wood aging or the simulation in the laboratory allows faster results and permits better control of temperature, humidity, and ultraviolet radiation, but several differences are registered, and its results tend to be less reliable, especially in the long term [5–9]. In addition, artificial aging does not consider other factors that may affect exposure in natural environments, such as biotic factors, seasonal differences, pollution, and other chemical characteristics of the local atmosphere such as acids and salts. For the above reasons, it will always be important to study the natural aging of wood exposed to real weathering and service conditions.

Sandak et al. [10] exposed several wood samples to natural weathering in distinct locations and evaluated the aesthetic, chemical, and physical changes in the wood using different techniques. This study concluded that the most significant changes, in the northern hemisphere, were observed for samples exposed to the south, followed by the east and west directions. The wood elements exposed to the north were less degraded, especially considering the chemical changes measured with infrared spectroscopy. Prieto et al. [11] analyzed a set of wood facades located in the southern hemisphere, and the most critical orientation was also facing the equator—the facades that were facing N/NE/NW reached the end of their useful life earlier, at 34 years, followed by S/SE/SW (35 years), W (36 years), and E (39 years).

Wood can be of several species, and even within species it is an anisotropic material with many heterogeneities. The existing visual grading standards are mainly oriented to projects with new wood. In this sense, limits are mainly imposed for various defects, because they make it difficult to fix the pieces, rather than the decrease in the resistance of the wood [12,13]. Since there are no specific standards for existing wood structures, the evaluations of timber structures end up being carried out by methods that each one of the specialists understands as more adequate and chooses to adopt.

To monitor wood elements in service and to plan the conservation actions to be implemented during its lifetime, it is important to periodically assess the integrity of its elements and to characterize the anomalies resulting from the various degradation agents. To have a quantitative parameter from the visual observation of wood damage, it is important to have a classification scale with guidelines that try to minimize the subjectivity of this classification, which is not usual in existing documents for wood assessment [14,15]. Sandak et al. [10] used a four-level scale for the classification of wood with few years of exposure to weathering, but, as it is based only on a description of images corresponding to the extreme status, it is very subjective in the intermediate levels, besides being insufficient for the classification of wood with more years of service. Prieto et al. [11] propose a classification of different levels of degradation for a set of anomalies, then calculate an index that represents the severity of degradation of timber claddings, and, finally, use it to make a service life prediction.

Before applying wood to buildings, various tests can easily be carried out to enable the classification of the resistance class according to the EN 338 standard [16] and perform a structural analysis according to the principles of EN 1995-1-1 [17]. In the impossibility of carrying out tests that allow the classification of the structural class of the wood, the specialists can also consider a visual strength grading such as the one presented in NP4305 [13]. In the wooden elements of a building, especially during its first years of operation, visual grading is the simplest way to follow the natural degradation of wood over time and identify the need to implement maintenance measures. In some cases, such as heritage or older building assessment, especially for safety structural assessment, some non-destructive tests (NDT), or even semi-destructive tests (SDT) or load tests [18], could be important complements to visual inspection to ensure a proper procedure [1,14,19] and avoid unnecessary safety measures. Some NDT that can be used to evaluate the wood performance in service are resistography, moisture content measurement, thermography, resistance drilling, pin penetration, ultrasound, and acoustic emission tests [1,18–24]. These non-destructive tests could be expensive, may require special equipment and trained personnel, could provide different kinds of information, and could be difficult to correlate with other classifications [23], so the choice of the most suitable method depends on the specific needs of the evaluation. Sometimes, the SDT could also be considered, and some small samples of wood should be removed to characterize physical and mechanical properties. Additionally, a combination of methods might be needed to have a complete assessment of the wood elements' condition, namely in old wood elements with structural functions. However, in contrast to classical laboratory tests, there is insufficient knowledge of individual factors' impact on NDT. For instance, the moisture content of wood elements may influence the results of ultrasonic waves, sclerometric, and resistance tests [22,25,26]. This could be especially crucial in areas with climate changes with moisture increase [27,28] and in areas with harsh conditions, such as near the sea where the moisture level is extremely high.

The study of treated and untreated timber power poles of energy networks made by Ryan et al. [29] verified that untreated poles require twice as many maintenance-related pole replacements over the analyzed period, which underlines the importance of treatment and maintenance in wood elements [30]. To study the wood degradation over time, it is important to have a grading guideline scale for wood in service that allows, based on visual inspections, assessment of the wood condition. Dietsch et al. [31] conclude that it is still necessary to develop simple application methodologies for the evaluation of wooden structures.

The main novelty of this work relies on the presentation of a new simplified but systematic methodology, based on visual inspection, for the classification of existing wood buildings, to allow cheaper, wider, and more frequent monitoring of wood elements in service and to promote its regular maintenance. As some wood buildings remain extremely expensive to maintain, it is important to find the most adequate and regular treatment. Towards that, an evaluation and classification scale should be prepared to guide the maintenance actions. The classification should separate abiotic and biotic degradation, as that distinction is important to the consequences and the nature of treatments. In general, the impacts resulting from the action of abiotic agents (such as rain, wind, and sun) are mainly aesthetic and do not have relevant implications in structural terms, but they can originate variations in the water content and cracks that help to create favorable conditions to potentiate the action of biotic agents [32]. Then, biotic agents can cause degradation of the wood's cellular structure, and, therefore, can produce much more serious effects, with significant mass and section losses [12,33–36].

The methodology will be tested on a 5-year-old hotel in northern Portugal, and this case will also be used to study what happened in new building wood elements, with different numbers of years in service, towards optimization of future wood maintenance plans and a determination of the most needed treatments and their best implementation timings. The application of the proposed assessment methodology will be necessary to target the state of degradation of wood buildings and then be able to reduce environmental impacts and costs. In future works, this methodology will be applied to obtain conclusions on the best time and strategy of maintenance for sustainable durability and life cycle cost optimization [37–39].

Furthermore, the presented visual classification scale could also be integrated with other technologies, such as image processing and artificial intelligence [40–45], to optimize wood production, assessment, and maintenance. Then, the classification could be made based on a visual observation in the field or based on image processing, either from pictures taken by humans or by pictures registered with unmanned vehicles.

## 2. Case Study

The case study is the main building of the Hotel FeelViana, located in Viana do Castelo, on the northern Atlantic cost of Portugal, very close to the Lima River and adjacent to a dune area. The hotel's main building has a rectangular development in plan, with two floors. Its four facades are oriented appreciably to the southeast, southwest, northwest, and northeast. On the ground floor, half-buried due to uneven terrain, there are shops, technical and administrative areas, a spa, an indoor pool, and events areas. On the raised floor there is a reception area, 46 rooms, a restaurant, a bar, and an outdoor pool. The building's structure is reinforced concrete on the ground floor and in wood on the upper floor, but the reinforced concrete structure is, in general, covered with wood.

Construction of the main building began in 2016 and the FeelViana Hotel went into service in May 2017. As the hotel has wood facades with different exposure situations, both in terms of solar orientation and in terms of rainwater contact, its analysis allows us to observe the differences resulting from the placing of the wood in service in diverse conditions of the surrounding environment. Additionally, in some areas wood maintenance treatments have already been carried out. In addition, because of some recent reformulations that have been carried out in some spaces of the hotel, the case study also allows us to observe the condition of elements with identical exposure and different years in service, thus being a case study with greater diversity, and that allows us to draw several conclusions relevant to the establishment and optimization of exterior wood maintenance plans.

*2.1. Characteristics of the Studied Wood*

The hotel has several wooden elements outside and inside its main building. Outside the building, there are elements in Scots pine (*Pinus Sylvestris*) and other woods, such as Japanese Cryptomeria and *Abies alba*. The pine is mostly present in the lath-slatted work that constitutes the facade around the hotel and in the horizontal and vertical elements of the balcony of the facade facing the sea.

This article is focused only on the study of the Scots pine wood used in the building's exterior as a coating. Scots pine, of scientific name *Pinus Sylvestris*, is a resinous wood from the coniferous family. Its origin is in Europe, and it is also present in Portugal, namely in the northeastern regions of the country [46]. The pine resistance is conditioned by the existence of knots and other natural singularities [6]. Although it is difficult to treat, due to its poor absorption [47], it is widely used, both indoors and outdoors [48], as it allows good workability [49]. Its density can vary depending on the geographical origin of the tree or even with the part of the tree under study [49].

The treatment scheme that the wood of the hotel took was the same for the different species, changing only in the colors of the varnishes applied. For the Scots pine, the initial treatment was performed as follows:

1. Wood-preserving biocide with fungicide action and certified insecticide (Axil 3000P);
2. One coat of a special primer with the appropriate color for each wood species (9100254-149—Croma Lacke);
3. Application of two spray coats of a special coating varnish with high water repellency, high UV resistance, elasticity, and water vapor permeability (931554-147—Croma Lacke);
4. Application of a coat, by spray gun, of a colorless varnish (reinforced with an additional UV filter) to meet aesthetic criteria and facilitate maintenance processes (931554-151—Croma Lacke).

The main facade of the hotel has an inclination in plant of about 30° in relation to the north, so that it can be considered as sensitively NE (north-east) oriented. Correspondingly, the opposite facade, facing the sea, will be considered SW (south-west) oriented and the smaller area facades of the building will then be NW (north-west) and SE (south-east) oriented.

Some zones of the hotel facade have architectural elements that protect the wood from the rain, so they can be classified in 3.1 class according to NP 3351 [50] (short humidification areas without water accumulation). However, there are also some unprotected outdoor areas that correspond to class 3.2, according to NP 3351 [50].

The considered case study is rich because it has wood elements with different solar exposures, risk classes according to NP 3351 [50], and service ages. For differentiation, the different study zones have been assigned as specified in Figure 1, and the given reference is composed as follows: two letters related to solar orientation (e.g., NE); one Greek letter related to the building area (α, β, ϒ, δ, ε and φ); year of placement/year of maintenance treatment (e.g., 2017/20). Figure 2 shows some pictures of some of those zones. To better understand the temperature and humidity conditions to which the hotel wood is subjected, these two parameters were monitored at some specific points of the hotel, through sensors placed at locations 1 to 8, indicated in Figure 1 with a green color.

*2.2. Weather Conditions*

In Viana do Castelo, a city located along the Atlantic coast, the climate is mild. An excerpt of a report from the *Instituto Português do Mar e da Atmosfera* (IPMA, Portuguese Institute of Sea and Atmosphere) on the normal climatological conditions of Viana do Castelo, between the years 1981 and 2010 [51], is presented in Table 1. It can be seen that the average monthly temperature varies between 9.7 °C and 20.8 °C, with absolute extremes of −5.1 °C and 39.5 °C, and the difference between the maximum and minimum monthly average temperatures is about 10 °C.

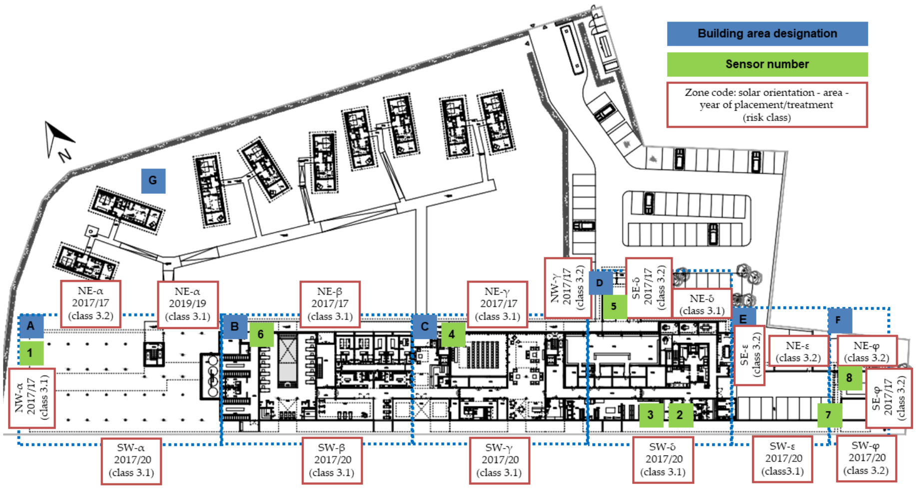


**Figure 1.** Map of the building with the location of the building areas, of the sensors, of the study zones, and of the risk classes.

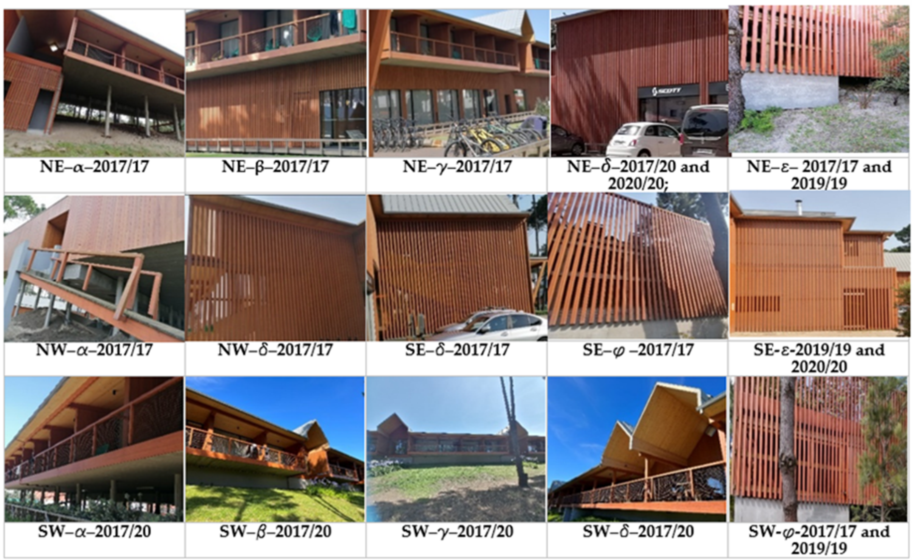


**Figure 2.** Images of the different areas of the facades of the main building of the hotel.

**Table 1.** Average temperature (TT), average maximum (TX), and minimum (TN) daily temperatures; higher daily maximum temperature value (Higher TX) and lower daily maximum temperature (Lower TN)].

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **TT (°C)** | 9.7 | 10.5 | 12.6 | 13.7 | 15.9 | 19.2 | 20.8 | 20.8 | 19.2 | 16.1 | 12.7 | 10.8 | **15.2** |
| **TX (°C)** | 14.6 | 15.5 | 17.9 | 18.5 | 20.7 | 24.5 | 26.3 | 26.4 | 24.8 | 20.9 | 17.3 | 15.2 | **20.2** |
| **TN (°C)** | 4.9 | 5.5 | 7.4 | 8.9 | 11.1 | 13.9 | 15.3 | 15.1 | 13.7 | 11.2 | 8.1 | 6.4 | **10.1** |
| **Higher TX (°C)** | 24.0 | 25.0 | 30.5 | 31.6 | 35.6 | 38.6 | 38.0 | 39.5 | 36.4 | 32.6 | 26.2 | 24.6 | **39.5** |
| **Lower TN (°C)** | −3.9 | −2.8 | −3.7 | −0.4 | 0.8 | 5.5 | 9.0 | 8.0 | 7.0 | 2.4 | −1.2 | −5.1 | **−5.1** |

It should be noted, however, that due to care taken in the design phase to increase durability, some of the wood elements of the facade are not directly exposed to rainwater. The high humidity in the region, with average monthly values always exceeding 74%, constitutes a risk of degradation relevant to wood. Moreover, with humidity above 85% in several weeks of the year, as is the case, the wood of the FeelViana hotel is in Eurocode class 3 [17].

## 3. Assessment Methodology

To propose an assessment methodology suitable for the inspection of wood elements in service it is important to have in mind the several types of degradation agents and the corresponding visual and importance impact. Towards that, an analysis of the wood degradation by abiotic (Section 3.1) and by biotic agents (Section 3.2) will be performed, with a particular reference to the visual manifestations of the several types of damage. That analysis is then used as a base for the proposal of an in situ wood AB classification scale, based on visual inspection, following the scheme presented in Figure 3, with the parameters A and B classified according to the scales that will then be proposed (Section 3.3).

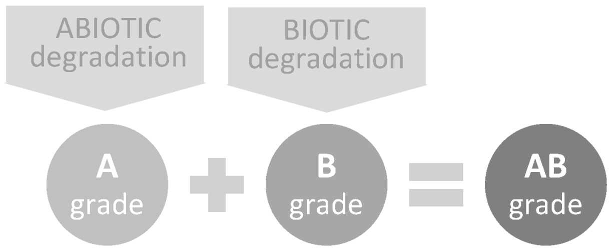


**Figure 3.** Proposed assessment methodology scheme.

### 3.1. Wood Degradation Abiotic Agents

Wood degradation of an abiotic nature can be caused by atmospheric agents, such as the sun, wind, and rain; chemical agents, such as those resulting from pollution action and cleaning products; or physical or mechanical agents, such as those associated with friction or shocks.

In a sheltered indoor or outdoor environment, the drying–humidification cycles to which wood is exposed during its service time force a variation in its water content and consequently its volume, creating internal tensions that could exceed the resistance in the perpendicular direction to the fibers and lead to splinting. Its occurrence usually results in the separation of growth layers (annular cracks) or in the separation according to their woody radii, exploiting the poor resistance of wood to efforts exerted in the connection between fibers. If the cracks are light this indicates that they are recent, since cracks become darker with time [32].

If the wood is placed in an external environment, in contact with rainwater, the drying–wetting cycle's effect is increased. The solar action, with ultraviolet and infrared radiation, increases the temperature of the wood outer layer, which loses moisture by evaporation in its surface layer. As the wood element interior is colder, this difference between the water content of the interior and the superficial layer originates tensions, causing the appearance of cracks or micro-cracks [34]. Ultraviolet rays cause the separation of the wood outer membrane from its cellular walls, leading to a wood surface fuzziness, which is visible through the greyish tone of the wood and, due to the leaching process and removal of this layer, the effect can penetrate deeper, eventually exposing the woody material of the underlying layer to the superficial one [52]. With prolonged exposure to the sun, the light wood becomes darker, and the dark wood becomes whiter, later presenting a dull greyish appearance with a whitish grain, as the cellulose becomes whitish due to the leaching of the lignin [34]. The infrared rays also cause cracking and the rise to the surface of the resin existing inside the wood itself [34]. Infrared rays combined with humidity and temperature changes can also lead to volume variation and the appearance of cracks [52]. Untreated wood is particularly susceptible to solar action, but in wood with varnishes and radiation paintings these effects cannot be ignored.

In maritime environments, besides the effect of rain, wood can absorb salts that can crystallize and increase the volume in the cellular wall, separating the fibers; however, on the other hand, seawater inhibits delignification, resulting from photodegradation, so there is no reduction in the relevant resistance capacity and the effects of this degradation are mainly aesthetic [53]. In coastal environments with significant wind, there can be a higher drag of particles in the air that can also cause some superficial wear of the wooden elements, with a consequent decrease in its useful section [52]. Besides these mechanical actions, there can also occur impacts in localized areas of the elements caused by extraordinary incidents. In areas particularly affected by rising humidity and condensation, wood degradation can also be accelerated. Areas in contact with the soil are particularly sensitive because of the wet–drying cycles, which, depending on precipitation and on its capacity of water retention and drainage, can be serious and, because of possible pH changes and chemical degradation, can create conditions favorable to degradation by biotic agents [35]. In countries where freeze–thaw cycles may occur, this effect can lead to the destruction of wood surface cells and significantly affect its resistance [34].

Although woods in general, and particularly resinous woods as is the case of Scots pine, are not extremely sensitive to chemical attack, there may be some problems in extremely acidic or alkaline environments [34]. In an acidic environment, cellulose hydrolysis occurs, which results in a decrease of the mechanical resistance, visually perceptible by the dark brownish color and crumbly texture [34]. As for alkaline environments, it promotes the dissolution of hemicellulose and the destruction of lignin, resulting in an incohesive and white aspect of the fibers, also decreasing the mechanical resistance of wood [52].

In areas with iron connections, wood cellulose oxidation can occur, which can be observed in situ by areas with a darker color that implies, locally, a lower mechanical resistance [34,52].

### *3.2. Wood Degradation Biotic Agents*

Wood biotic agents of degradation are also known as xylophages, since in Greek "xylo" means wood and "phage" means food. The main biotic wood degradation agents, the respective occurrence conditions, and their implications are synthetically presented in Tables 2 and 3 [12,34–36]. Table 2 is dedicated to the agents from the vegetal kingdom, such as bacteria and fungi xylophages, and Table 3 is dedicated to the agents from the animal kingdom, such as insect xylophages.

The colonization of wood by fungi and bacteria is only possible under favorable environmental conditions. Colonization by bacteria and micro-fungi is possible when there is water in the wood. Therefore, if the wood remains sufficiently moist and if the lighting and ventilation conditions are adequate, colonization by decay fungi can take place. Bacteria and fungi destroy part of the cellular structure but do not cause the immediate weakening of the wood; however, the wood becomes more porous, allowing its moisture content to increase [52]. Wood may also be attacked by animals, such as the marine xylophagous and the xylophagous insects described in Table 3, as well as by other types of animals, such as rodents or animals that nest or burrow in wood, such as woodpeckers.

**Table 2.** Xylophagous bacteria and fungi [12,34–36].

| Designation | Specie | Conditions of Occurrence | Visual Aspect | Other Features | Implications |
|---|---|---|---|---|---|
| Molds | Not wood specific—occurs in any material with sufficient water content | Appears mainly in softwoods. They develop mainly outdoors with water content above 25–30%, with temperatures between 20 °C to 28 °C and poor lighting. Indoors, it appears only in areas with infiltrations | Stains of various colors on the surface of wood, with colors between white and black (they develop as a result of high relative humidity or by condensation of water vapor) | They develop through contamination by wood that has already been attacked or through the germination of spores carried by animals, wind or tools, feeding on components present in the woody cells of the wood | Easily removable by surface cleaning |
| Chromogenic fungi | | | Bluish to black stains (sometimes pinkish or greyish) on sapwood, with variable intensity and depth | | They do not decrease resistance, only causing changes in color and increased permeability, with an increased likelihood of rot fungus developing |

**Table 2.** *Cont.*

| Designation | | Specie | Conditions of Occurrence | Visual Aspect | Other Features | Implications |
|---|---|---|---|---|---|---|
| Rot fungi or lignivorous | Soft rot fungi | Micro fungi | More common in hardwoods. It needs a lot of moisture to develop, which is why it is more common in woods in contact with the ground or water, but not saturated | With fractures in cubes, with a shade between gray and brown. In dry wood, it has a normal appearance, but when chipped by a knife it breaks into fragments | Musty smell, changes in configuration (disintegration), visual changes (change in colors and soft areas), hollow sound, weight loss, loss of strength and change in water content | Superficial softening of the wood, although it can also cause damage in depth and lead to the total destruction of the structure |
| | Brown rot fungi—wet | Fungi of the genus Basidiomycetes | It attacks more resinous woods with water content higher than 20%, but not saturated | It can be called cubic rot because when attacking the components it causes fiber retraction, resulting in cracking in the element, in the transverse and longitudinal direction (forming smaller cubes in the dry brown rot than in the wet one). | | Like white rot, it develops in the cellular cavities of wood, but with the difference that they consume only hemicellulose and cellulose, not attacking lignin |
| | Brown rot fungi—dry | Fungi of the species Serpula lacrymans | Slightly moist but not saturated areas. Rapid propagation due to the ability to grow even over elements with no nutritional value for the fungus (masonry and mortar) | | | |
| | White rot fungi | Fungi of the genus Ascomycetes and Basidiomycetes | It attacks more hardwoods with water contents above 20%, but not saturated. | Whitish appearance with a fibrous texture. This appearance results from the cellulose, which after the attack remains as a residual component (the lignin is completely destroyed). | | They develop in the cellular cavities of the wood and attack the hemicellulose and lignin, damaging the wood in terms of mechanical resistance |

**Table 3.** Xylophagous animals [12,34–36].

| Designation | | Specie | Conditions of Occurrence | Visual Aspect | Other Features | Implications |
|---|---|---|---|---|---|---|
| Woodworms (or beetles) | | Anobium punctatum (De Geer), Order Coleoptera, family anobiidae | Attacks resinous or hardwood sapwood in areas of high humidity | Visible small circular holes (1 to 4 mm) for insects to exit. Sawdust mounds are also common, both inside the galleries and next to the holes. | Flying insects that lay their eggs in the pores or crevices of the wood, and whose larvae feed on the woody material in the wood. They are larval cycle insects with 4 stages of development: egg, larva, pupa and adult. You can hear the larvae eating the wood. It is in the larval stage that they cause the destruction of wood by excavating galleries | Generally, does not lead to a large decrease in mechanical strength. |
| | | Lyctus (Lyctus sp.) order Coleoptera, family Lyctidae | Exclusively attacks hardwood sapwood rich in starch, in areas with high humidity | | | |
| | | Big woodworm—Hylotrupes bajulus L, order Coleoptera, famiily Cerambycidae | Attacks resinous woods and mostly just sapwood | Visible oval holes (6 to 10 mm) for insect exit. Due to the pressure of the sawdust inside the galleries, the surface wrinkles and blisters, make it easy to lift with a blade. | | Its attack can have serious consequences at the structural level since there is a great decrease in the section. |
| Marine xylophages | Crustaceans | The most common are the species Limnoria (also called "sea flea") | Woods in a maritime environment of clear or turbid saline waters | | | They attack the surface of the wood, making holes 1 mm deep. |
| | Molluscs | They belong to the Terediniceus family (the most important species is the Teredo) | Woods in a maritime environment with clear saline waters | They are detected by the holes they leave in the surface of the wood, although the degree of external attack does not correspond to the gravity found inside the wood. | | They attack the inside of the wood and perforate it, leaving it with a honeycomb appearance. Very high section reduction, which could lead to collapse. |

**Table 3.** *Cont.*

| Designation | Specie | Conditions of Occurrence | Visual Aspect | Other Features | Implications |
|---|---|---|---|---|---|
| Termites | Insects from the Isoptera group (Reticulitermes lucifugus Rossi are the most abundant in continental Portugal) | Water contents greater than 20% but not saturated. They attack all wood species, with particular emphasis on pine. It usually starts on the ground floors and can go up to the rest if food is scarce on the lower floors or there is a wooden connection to the floors (e.g., Pombaline cage). More usual in areas with infiltration problems | Wood veneer appearance (such as "millefeuille" cake). In the galleries formed by the termites, observable by using a knife to lift the wooden film that protects them, sawdust is not found, but earthy concretions. Earth galleries can be seen on the wood or masonry, or swarms of winged insects | Termites are social and are organized into 3 castes, each with its functions for the community. They lose their wings before laying eggs between May and August. | The diagnosis is often only given when the attack has already extended to the entire structure. |

### *3.3. Wood Evaluation—Proposed Scale for Classification of Elements in Service*

To classify the condition of wood in service, based on visual observation, in an objective way, an AB classification scale was developed, composed of the classification of two parameters (Figure 3)—parameter A, regarding the wood degradation classification due to abiotic agents, and parameter B, regarding the wood degradation classification due to biotic agents. In each of these parameters, four distinct levels are considered, from 0 to 3, each one of them with specific characteristics. In that scale, the value 0 corresponds to the best condition, with no degradation manifestations, and the value 3 corresponds to the worst situation. The proposed classification scale for in situ visual assessment of wood was developed considering the previously presented considerations and is presented in Tables 4 and 5, for parameters A and B, respectively. Observing one of the listed characteristics at a higher level is enough to grant the grading status. However, if these manifestations are not relevant and occur in less than 10% of the observed area, they may be disregarded in the attribution of the classification grade.

**Table 4.** Visual classification A on wood degradation by abiotic agents.

| A0 | A1 | A2 | A3 |
|---|---|---|---|
| > After wetting, drops of water are visible on the surface.<br>> Surface cracks with a maximum length of 600 mm<br>> Cracks passed only at the ends and with a maximum length of 600 mm (no more than 1 per m) | > After wetting, no drops of water are visible on the surface<br>> Surface with some wear (e.g., abrasion from windblown sand or loss of cross-section at edges)<br>> Surface cracks with a maximum length of 900 mm<br>> Cracks passed only at the ends and with a maximum length of 900 mm (no more than 1 per m)<br>> Openings in connecting zones | > Peeling of the surface layer (separation of the outer membrane of the wood from its walls caused by UV rays)<br>> Cracking longer than 900 mm<br>> Cracks passed beyond the tops<br>> Stains only in the vicinity of old iron connections and dark in color | > Cracks with an opening greater than 1 mm |

In parameter A, grade A0 corresponds to wood in the best condition, such as the moment of placing in service, when the water repellence given by the treatment is still maintained and can be verified by observing drops of water on the surface after wetting. The cracks must respect the characteristics indicated in the NP 4305 standard [13] to be in the best class, class EE. When the crack has characteristics that no longer allow the classification in class EE, but still allow classification in class E, specified in NP 4305 standard [13], the associated status is A1. Classes E and EE correspond globally to classes C18 and C35 of EN 338 standard [16]. If the cracks observed do not even allow the assignment of class E of the NP 4305 standard, the score will become more serious, corresponding to a level A2 or A3.

On the other hand, if the roughness observed indicates some surface wear, the status will also be A1, and if there is peeling of the surface layer, which is more difficult to repair, the status will be A2. If the observable cracks have a considerable crack opening greater than 1 mm, the classification of the A parameter should be at least A3.

**Table 5.** Visual classification B on wood degradation by biotic agents.

| B0 | B1 | B2 | B3 |
|---|---|---|---|
| > No stains | > Stains removable by surface cleaning | > Bluish to black stains (sometimes pinkish or greyish) on sapwood, with varying intensity and depth<br>> Small and circular holes, smaller than 4 mm, with mounds of sawdust nearby<br>> Holes with 1 mm deep by "sea fleas" (sea zones only) | > Whitish appearance with a fibrous texture.<br>> Splitting in the transverse and longitudinal direction (forming cubes)<br>> Oval holes, over 5 mm, for insect exit and wrinkled wood easy to lift with a blade<br>> Veneer appearance<br>> Wood destroyed with a honeycomb appearance<br>> Musty odor<br>> Dry crumbled areas or soft damp areas<br>> Sounds hollow<br>> Areas with burrows or nests |

Analogously to what was done for abiotic damage, a classification regarding biotic agents is also proposed. In parameter B, the B0 status should be assigned whenever there are no stains evidencing biotic degradation. Dark stains in the vicinity of iron bonds were left in parameter A because they are associated with chemical reactions with iron and do not correspond to the action of organic agents. When the observable stains are removable by surface cleaning the status should be B1, because biotic degradation will be due to small mold or vegetation, thus being of less severity. Grade B2 should be assigned when the stains show the action of chromogenic fungi or small woodworms, as described previously in Tables 2 and 3. The damages resulting from the action of the remaining degradation agents should refer to a status B3, the worst level of classification, because they may have serious implications, such as a significant loss of the wood section.

As the abiotic degradation is not as serious as the biotic one, the level of the assigned AB scale is more serious the higher the number associated with the letter B. In cases where the levels of A and B parameters are the same, the grade is more serious for those with a higher number assigned to the letter A.

The rating scale was not developed for wood elements with structural functions. However, in the case of relevant damage observed in structural elements, it is still important that the evaluator makes an assessment that considers its localization in the element and the level of effort present in the area. Additionally, the inspector may also recommend more tests, monitoring, and complementary studies that may help clarify any doubts about safety in critical zones.

With this methodology for inspection and visual damage classification of non-structural wood elements, a detailed damage assessment was achieved. This will allow us to identify better treatment plans and maintenance costs, bearing in mind the need for regular maintenance of wooden elements in an outdoor environment even in the first years of service.

The type of required treatment is dependent on the type of degradation observed, and therefore when the wood is deteriorated with abiotic agents, such as cracks, peeling or splitting, it requires sanding and treatment with paint or resins, and when the wood deterioration shows signs of biotic agents action it requires biocides.

## 4. Results and Discussion

### *4.1. Temperature and Humidity Measurement*

The results of temperature and humidity measurements made by sensors 1 to 8 placed in the case study, with the location specified in Figure 1, are shown in graphs presented in Figures 4 and 5. For humidity, the used devices have a measuring range of 0 to 100% with an accuracy of +/−3% at 25 °C. For temperature, the used devices have a measuring range of −20 °C to +70 °C with an accuracy of +/−0.5 °C. Those data were registered in 2022, between April 18 and June 24. Table 6 summarizes the humidity range and temperature variation recorded in each sensor.

The results recorded by the sensors installed in the hotel, in Table 6, present several periods in which the relative humidity exceeds 85%; thus, the relevance of the service level 3 classification according to Eurocode 5 can be confirmed [17].

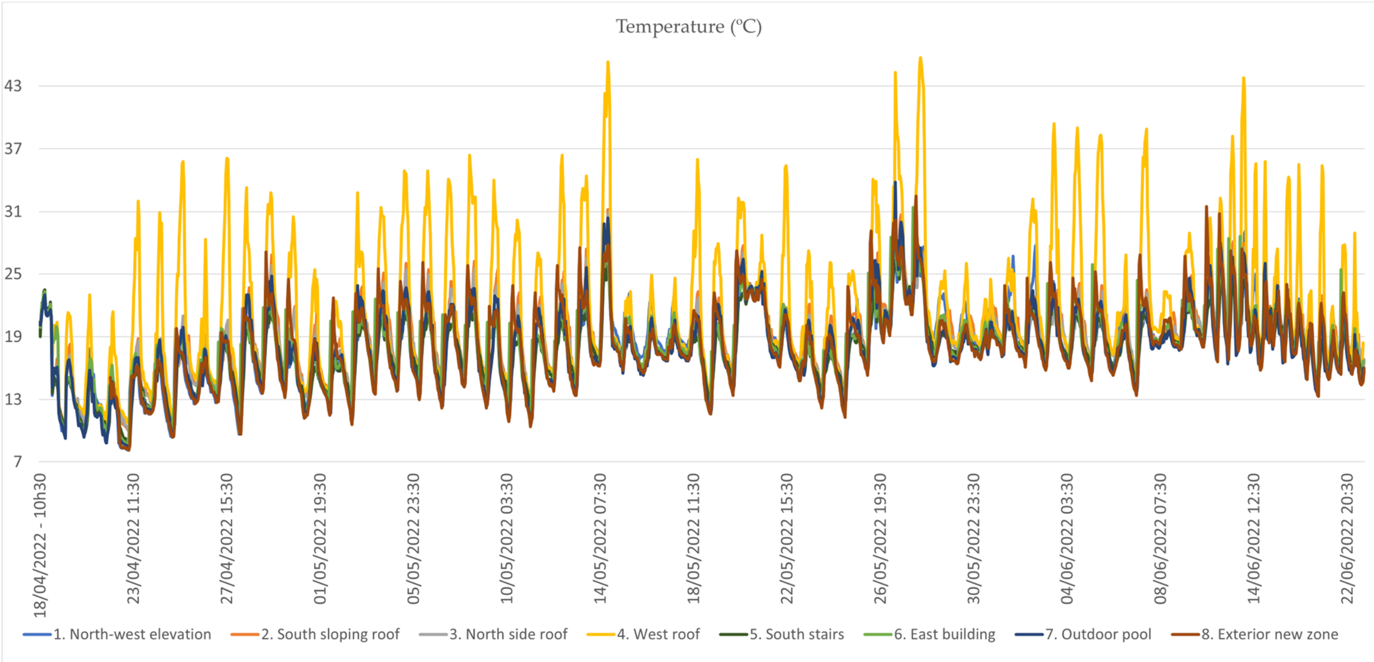


**Figure 4.** Temperature variation in hotel sensors between April and June 2022.

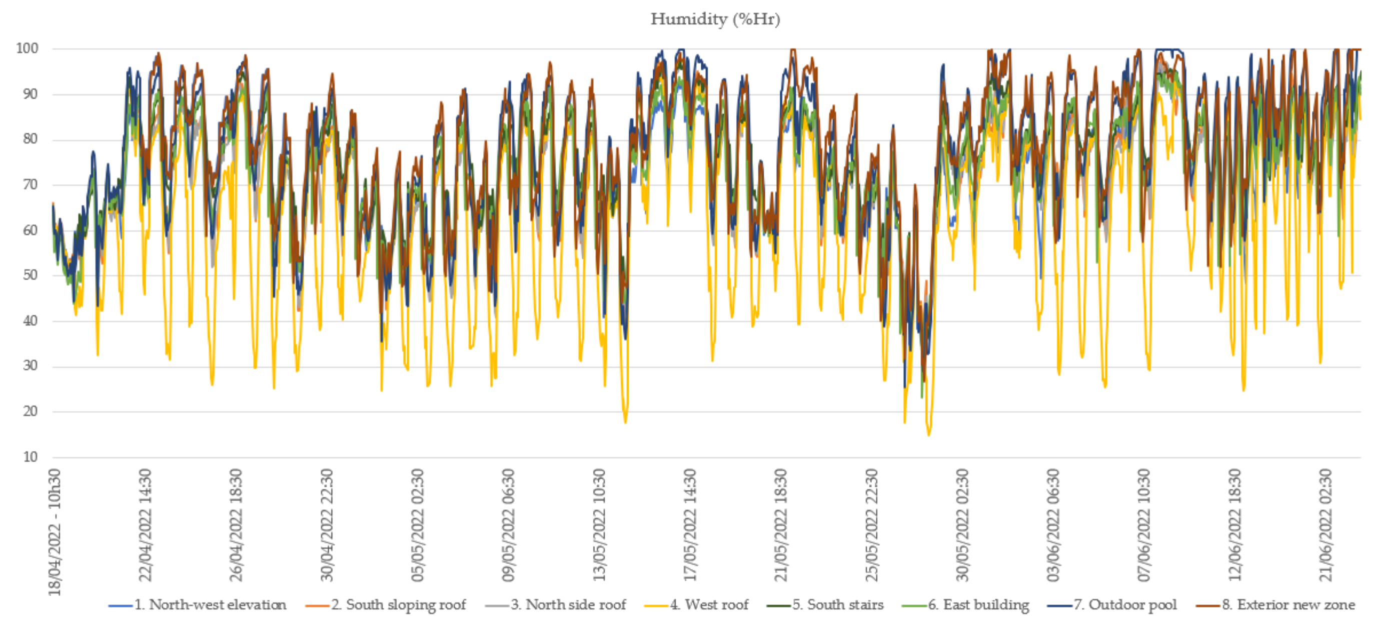


**Figure 5.** Humidity variation in hotel sensors between April and June 2022.

The results recorded in sensor nº 4, located in a chapel on the roof of the building oriented to SW at the highest elevation of the building, facing the sea at a high level and exposed to direct sunlight for several hours of the day, stand out significantly from the others, mainly by reaching much higher temperatures (maximum temperature of 45.7 °C, higher than the maximum of any other sensor, which is 33.8 °C) and significantly lower relative humidity (minimum humidity of 14.8%, lower than the minimum of other sensors which is 23.3%).

**Table 6.** Temperature and humidity variation at hotel sensors—April to June 2022.

| Sensor Location | T Average (°C) | T Max (°C) | T Min (°C) | ΔT (°C) | H Max (%Hr) | H Min (%Hr) | ΔH (%) |
|---|---|---|---|---|---|---|---|
| 1. North-west elevation: north-west façade of the hotel's main building | 18.3 | 30.5 | 8.1 | 22.4 | 99.2 | 33.3 | 65.9 |
| 2. South sloping roof: south facing south-west building façade | 18.8 | 31.2 | 9.5 | 21.7 | 99.3 | 35.0 | 64.3 |
| 3. North side roof: south-west façade of the building facing north | 18.5 | 30.9 | 9.4 | 21.5 | 97.5 | 35.4 | 62.1 |
| 4. West roof: chapel facing south-west at the highest elevation of the building | 21.4 | 45.7 | 10.0 | 35.7 | 99.0 | 14.8 | 84.2 |
| 5. South stairs: under the stairs at the entrance to the main building, facing south | 17.6 | 28.2 | 8.8 | 19.4 | 97.7 | 30.9 | 66.8 |
| 6. East building: north-east façade of the building, further north | 18.2 | 31.4 | 8.8 | 22.6 | 95.0 | 23.3 | 71.7 |
| 7. Outdoor pool: outdoor swimming pool area, facing south-west | 17.8 | 33.8 | 8.3 | 25.5 | 99.9 | 25.6 | 74.3 |
| 8. Exterior new zone: north-eastern façade of the building, near the southern top | 18.3 | 32.5 | 8.1 | 24.4 | 99.9 | 26.8 | 73.1 |

In the measurements taken at the other sensors during the monitored period, temperatures varied between 8.1 and 33.8 °C and relative humidity between 25.6 and 99.9%. The measurement of temperature and humidity at the site will be extended for a longer period to allow a characterization that encompasses different seasons of the year. In any case, it is already clear from the data presented that in the environment where the Scots pine wood under study is implanted, the thermal variation order of magnitude may be higher than 30 °C and the relative humidity variation may be higher than 80%.

### 4.2. *Evaluation of the Facades' Wood Degradation*

The different areas of the building's facades' wood elements, previously defined (Figure 1), were classified according to the proposed AB scale, based on an inspection made in July 2022. In the zones in service since 2019 or later, no signs of degradation were found, and the classification assigned corresponded to grade A0B0. The image in Figure 6 shows one of these zones, where it is possible to see some drops of water on the surface after watering the wood, thus evidencing its water-repellent capacity.

**Figure 6.** Wood elements in grade A0B0 (photograph in zone NE-**φ**-2017/17).

The other zones, with some evidence of degradation, were classified at other levels of the considered scale. The FeelViana pine wood facade classification from 2022 is summarily presented in Figure 7, where the references of each of those zones are associated with the grades assigned. Figure 7 also shows some illustrative pictures (corresponding to the areas referenced in bold) and indicates the risk class of each of the zones, according to NP 3351 [50]. The interpretation of the results presented in Figure 7 allows a comparison of the grade of identical elements with several ages, maintenance actions, and exposures to sun and rain. Comparing the A0B0 classification of the NE-φ-2019/2019 zone (Figure 6) with the A1B1 of the adjacent NE-φ-2017/17 zone (Figure 7), it is possible to observe that 2 years more of weathering exposure, in an unprotected zone (class 3.2 [50]), are sufficient for a change in one level of the B parameter of the proposed scale. The NW facade reached the A2B2 condition after about 5 years in service, so the treatment may already be slightly less demanding than in SE, namely in terms of surface regularization. In the NE facade, the unprotected zones (class 3.2) are in an A0B0 condition after 3 years in service and after 5 years in service are, generally, in better condition than in the NW facade. However, occasionally it also reached A2B2 condition after 5 years, as happened in NE-α-2017/17 zone.

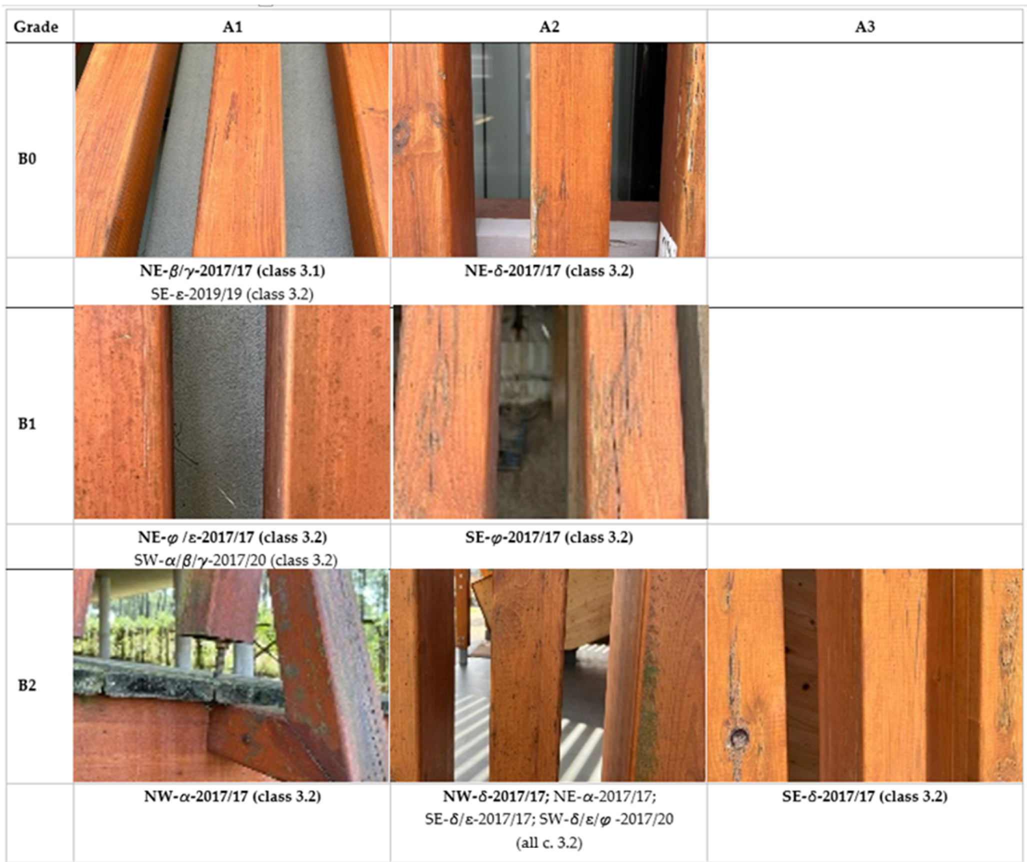


**Figure 7.** Hotel zones classified in each of the different condition statuses (areas illustrated in the photographs are marked in bold) of the proposed scale, in addition to A0B0—the grade can be read using the name of the column and the name of the line.

Considering the classification assigned in the inspection carried out, it can be verified that the most critical zones are generally those facing south, i.e., towards the equator line, following what is mentioned in the bibliography. The worst-performing area is SE-**d**-2017/17, corresponding to the side area of the stairs of the main entrance, oriented between SE and SSE, with a classification of A3B2. On the other side of the same stairs, in the NW-δ-2017/17 zone, oriented between NW and NNW, an unequivocal difference is evident, with less cracking and smaller opening of the cracks, so the grade assigned was A2B2.

### 4.3. Study of Color Change and Analysis of Its Possible Correlation with the Proposed Evaluation

With ultraviolet radiation, wood properties change over time. The color change in the wood under analysis was studied based on measurements made with a Konica/Minolta colorimeter, model "Chroma Meter CR-400" (which achieves exceptional accuracy in terms of inter-instrument agreement: CR-400: ΔE*ab within 0.6 repeatability: within ΔE*ab 0.07). In the colorimeter used, the color is specified based on the CIELab system [54]. According to the CIELab system, $L^*$ corresponds to the luminosity of the material, with 100 being an ideal white and 0 a pure black. Parameter $a^*$ indicates the degree of redness (if positive in value) or greenish appearance (if negative). The $b^*$ parameter indicates the degree of yellowing (if positive) or blueish (if negative). A unit of change in either parameter can be considered as an approximation of a typical noticeable difference for uniformly colored objects under ideal lighting.

For color comparison between the different zones, the first equation that CIELab suggested in 1976 was adopted to simplify the calculations, since those suggested subsequently, despite being more accurate, are more complex. The color variation measured with the colorimeter will thus be quantified in JND (Just Noticeable Difference) and calculated by the following equation [55–57]:

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

where:

$\Delta L^*$ represents the difference between the luminosity of the parts;

$\Delta a^*$ represents the difference between the magenta-green values;

$\Delta b^*$ represents the difference between the yellow-blue values.

The general long-term trend is for the surface layer of wood elements to acquire a greyish color, becoming darker over time (lower L* value), less red (lower a* value and closer to zero), and less yellow (lower b* value and closer to zero) [5]. However, according to the same source, it is important to note that short-term effects often did not correspond to long-term trends.

Since wood is a natural product, the color may have significant variations for different areas where the measurement is made. Therefore, several measurements were performed in each of the observed areas. Table 7 presents the average results of the measurements performed with the colorimeter on Scots pine woods with different sun exposure and degradation grades, at two separate times—June 14 and 29 July 2022, as well as the variation for each zone in the 45 days that correspond to that period (Δ 45 days). The zone with higher average values of the three parameters ("L", "a" and "b") is the NE-α 2019/19, corresponding to the hotel kids-club zone, which is shaded by the high floor covering and therefore will be the closest to the original coloration, since a sample equal to the original ones is not available. In the areas where the wood entered in service in the year 2020 (NE-δ-2020/20 and SE-ε-2020/20), despite being more recent, the color has already suffered more photodegradation due to greater exposure to sunlight, revealed by the inferior values obtained for "L", "a", and "b" parameters. Therefore, Table 7 also presents an analysis of the color variation measured in the various zones, ΔE*, calculated with Equation (1), in relation to the color recorded in the NE-α-2019/19 zone.

The variations between the measurement of 14 June and the measurement of 29 June, corresponding to a time difference of a month and a half, almost always show a very small lowering of the parameters "L", "a", and "b", despite some exceptions. However, although the time space between the two measurements is relatively short, the changes observed are quite evident in some cases. In any case, a total variation of color was always recorded in the same direction, with an ΔE* between 0.36 and 2.34, which seems to be more pronounced in cases with less sunlight and more signs of degradation by biotic agents. By analyzing the zones in increasing order of the values of ΔE*, related to the considered base NE-**a**-2019/19 (the order in which the zones are presented in Table 7), despite some exceptions, a certain relationship can be seen between the order of color and the severity of the grade of degradation expressed by the given AB classification. Therefore, the colorimeter measurements showed that it can be useful as a complementary instrument to the wood visual inspection. However, it is not recommended to limit the analysis exclusively to the color parameter.

**Table 7.** Data recorded with the colorimeter in the wood of different hotel zones.

| Zone Reference | | NE-α 2019/19 | NE-φ 2019/19 | NW-δ 2017/17 | NE-δ 2020/20 | SE-ε 2020/20 | NE-β 2017/17 | SE-φ 2017/17 | NW-α 2017/17 | NE-φ 2017/17 | SE-δ 2017/17 | SW-δ 2017/20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Grade** | | **A0B0** | **A0B0** | **A2B2** | **A0B0** | **A0B0** | **A1B0** | **A2B1** | **A1B2** | **A1B1** | **A3B2** | **A2B2** |
| 14/6/22 | L | | 46.53 | 49.10 | | | 44.44 | 43.36 | 45.23 | 42.75 | 43.67 | 44.27 |
| | a | | 25.45 | 19.59 | | | 20.40 | 18.28 | 18.75 | 19.08 | 16.63 | 15.78 |
| | b | | 33.32 | 32.01 | | | 29.44 | 27.08 | 27.19 | 26.95 | 26.03 | 25.74 |
| 29/7/22 | L | | 46.97 | 48.42 | 46.93 | 46.83 | 44.66 | 43.75 | 43.97 | 42.77 | 43.48 | 44.57 |
| | a | | 25.49 | 18.94 | 20.52 | 20.08 | 20.20 | 18.35 | 17.77 | 18.76 | 16.32 | 15.53 |
| | b | | 32.98 | 32.22 | 31.11 | 30.32 | 29.65 | 26.81 | 25.48 | 25.30 | 25.76 | 25.88 |
| Δ 45 days | ΔE* | | 0.56 | 0.96 | | | 0.36 | 0.39 | 2.34 | 1.68 | 0.46 | 0.41 |
| ΔL* p/NE-α-2019/19 | | 0.00 | −1.16 | 0.30 | −1.19 | −1.30 | −3.47 | −4.38 | −4.16 | −5.36 | −4.64 | −3.56 |
| Δa* p/NE-α-2019/19 | | 0.00 | 2.11 | −4.44 | −2.86 | −3.30 | −3.18 | −5.03 | −5.62 | −4.62 | −7.07 | −7.85 |
| Δb* p/NE-α-2019/19 | | 0.00 | −3.85 | −4.60 | −5.72 | −6.50 | −7.18 | −10.01 | −11.34 | −11.52 | −11.07 | −10.94 |
| ΔE* p/NE-α-2019/19 | | 0.00 | 4.53 | 6.40 | 6.50 | 7.40 | 8.58 | 12.03 | 13.32 | 13.52 | 13.92 | 13.93 |

## 5. Conclusions

From the analysis of the wood degradation process induced by abiotic and biotic agents, an AB scale was proposed for classifying wood in service based on its visual observation. That classification has two parameters—parameter A, relative to degradation by abiotic agents, and parameter B, relative to degradation by biotic agents, each one with a numeric grade between 0 (best condition) and 3 (worst condition). Since biotic degradation has more severe implications than abiotic degradation, the grade assigned will correspond with more severe conditions, as the number associated with parameter B is higher than the status associated with parameter A. The evaluation proposed can be easily performed in other situations, allowing reproducibility in large-scale field monitoring campaigns. Furthermore, its relationship with the repair needs allows us to prepare and optimize maintenance plans and improve the overall performance of the building.

From the observed conditions on the pine wood facade of FeelViana hotel, subject to five years of natural aging, some interesting conclusions can be drawn for the development of the maintenance plans for the analyzed building and for others with similar conditions. Bearing in mind the date of entry into service and the date of the treatments performed, as well as the solar and weathering exposure of each evaluated area, the following conclusions can be drawn:

- The pine elements in service since the hotel opening date, 2017, that are protected from the rain (exposure class of 3.1 [50]), do not present degradation by biotic agents in 2022 and were classified at the best level of grade B. This fact highlights the importance of the protection of the pine provided in the architecture project, which protects the wood from humidification, wind, and sun, delaying the development of wood degradation by biotic agents.
- Although the inspected hotel has only been in service for 5 years, biotic degradation manifestations were recorded on all the different solar orientations of the building facades, reaching B2 status in some areas. That highlights the need for regular maintenance of wooden elements in an outdoor environment.
- The condition of the horizontal elements is worse than the condition of the vertical ones in the same zone, as seen in the SW facade, due to water accumulation. Thus, the wood maintenance treatment must be more regular in horizontal pieces.
- On the SW oriented facade, facing the sea, there are already areas in the A2B2 grade a little more than 2 years after the last maintenance treatment. Therefore, wood maintenance treatment should be regularly performed, with intervals of 1 to 2 years, particularly due to the high exposure to the sun and rainwater.

- A careful periodicity of treatment will be also necessary in the SE orientation, where after about 3 years there are no signs of biotic degradation, but after about 5 years there are already areas in B2 grade.
- The facade where the treatment will be less demanding corresponds to the protected areas (class 3.1) facing NE, with the best condition, A0B0, after about 3 years and the worst grade of the zone, only A1B0, after about 5 years in service.
- The most critical areas are, in general, those orientated to the equator line (S). The SW facade was treated after 3 years in service and after 2 more years it shows similar treatment needs or, occasionally, even greater than in the NE facade, which has about 5 years in service without maintenance treatment. Therefore, the need for maintenance treatments is much higher in the SW than in the NE orientation. Accordingly, during the service phase, the number of wood treatments on the south facades should be approximately double the number of wood treatments needed on the other facades.
- Measurements made with the colorimeter showed that it can be a complementary instrument to the visual inspection of woods along the service life, since the color variation of the tested pine wood is significant, even with a short time interval of 45 days. These variations are more relevant when their biotic degradation is present; however, based on the achieved results, it is not recommended to limit the analysis exclusively to the color parameter.

The proposed scale has been implemented on the Scots pine facades of the case study described—the main building of FeelViana hotel, located on the Portuguese Atlantic coast. The maintenance and life-cycle cost optimization based on the assessment results will be now tested in order to evaluate it and identify potential improvements. Some of the future research directions will also be the application of the methodology in other types of wood species and elements, as well as under different environments and varying climatic conditions. Beyond, another aim for the future could be computer training for the automatic classification of wood elements based on images taken by humans or even by unmanned aerial vehicles.

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## References


1. Bajno, D.; Grzybowska, A.; Bednarz, Ł. Old and Modern Wooden Buildings in the Context of Sustainable Development. *Energies* **2021**, *14*, 5975. [CrossRef]
2. Xu, H.; Li, J.; Wu, J.; Kang, J. Evaluation of Wood Coverage on Building Facades Towards Sustainability. *Sustainability* **2019**, *11*, 1407. [CrossRef]
3. Xu, H.; Li, J.; Li, M.; Wu, J. A Statistics-Based Study on Wood Presentation of Modern Wood Building Facades. *MATEC Web Conf.* **2019**, *275*, 01016. [CrossRef]
4. Gradeci, K.; Labonnote, N.; Time, B.; Köhler, J. A probabilistic-based methodology for predicting mould growth in facade constructions. *Build. Environ.* **2018**, *128*, 33–45. [CrossRef]
5. Kropat, M.; Hubbe, M.A.; Laleicke, F. Natural, Accelerated, and Simulated Weathering of Wood: A Review. *BioResources* **2020**, *15*, 9998–10062. [CrossRef]
6. Reinprecht, L.; Mamoňová, M.; Pánek, M.; Kačík, F. The impact of natural and artificial weathering on the visual, colour and structural changes of seven tropical woods. *Eur. J. Wood Wood Prod.* **2017**, *76*, 175–190. [CrossRef]
7. Elam, J.; Björdal, C.G. Degradation of wood buried in soils exposed to artificially lowered groundwater levels in a laboratory setting. *Int. Biodeterior. Biodegrad.* **2023**, *176*, 105522. [CrossRef]
8. Herrera, R.; Arrese, A.; Hoyos-Martinez, P.L.; Labidi, J.; Llano-Ponte, R. Evolution of thermally modified wood properties exposed to natural and artificial weathering and its potential as an element for façades systems. *Constr. Build. Mater.* **2018**, *172*, 233–242. [CrossRef]
9. Mao, J.; Abushammala, H.; Kasal, B. Monitoring the surface aging of wood through its pits using atomic force microscopy with functionalized tips. *Colloids Surf. A Physicochem. Eng. Asp.* **2021**, *609*, 125871. [CrossRef]
10. Sandak, J.; Sandak, A.; Riggio, M. Characterization and Monitoring of Surface Weathering on Exposed Timber Structures with a Multi-Sensor Approach. *Int. J. Archit. Herit.* **2015**, *9*, 674–688. [CrossRef]
11. Prieto, J.; Silva, A. Service life prediction and environmental exposure conditions of timber claddings in South Chile. *Build. Res. Inf.* **2020**, *48*, 191206. [CrossRef]
12. Cruz, H. Inspeção, avaliação e conservação de estruturas de madeira [Em linha]. In Proceedings of the 1a Jornada de Materiais de Construção, Porto, Portugal, 6 April 2011. (In Portuguese)
13. *NP 4305:1995*; Madeira Serrada de Pinheiro Bravo para Estruturas Instituto Português da Qualidade. IPQ: Caparica, Portugal, 1995. (In Portuguese)
14. Cruz, H.; Yeomans, D.; Tsakanika, E.; Macchioni, N.; Jorissen, A.; Touza, M.; Lourenço, P.B. Guidelines for On-Site Assessment of Historic Timber Structures. *Int. J. Archit. Herit.* **2015**, *9*, 277–289. [CrossRef]
15. Uzielli, L. Wood Science for Conservation of Cultural Heritage—Florence 2007. In Proceedings of the International Conference held by COST Action IE0601 in Florence (Italy), Firenze, Italy, 8–10 November 2007; Firenze University Press: Firenze, Italy, 2009. [CrossRef]
16. *BS-EN 338*; Structural Timber—Strength Classes. BSI Standards, CEN (Comité Européen de Normalisation—European Committee for Standardization): Brussels, Belgium, 2016; ISBN 978 0 580 83526 1.
17. *NP EN 1995-1-1*; Eurocode 5: Design of Timber Structures. CEN (Comité Européen de Normalisation—European Committee for Standardization): Brussels, Belgium, 2006.
18. Arriaga, F.; Osuna-Sequera, C.; Esteban, M.; Íñiguez-González, G.; Bobadilla, I. In situ assessment of the timber structure of an 18th century building in Madrid, Spain. *Constr. Build. Mater.* **2021**, *304*, 124466. [CrossRef]
19. Feio, A.; Machado, J.S. In-situ assessment of timber structural members: Combining information from visual strength grading and NDT/SDT methods—A review. *Constr. Build. Mater.* **2015**, *101*, 1157–1165. [CrossRef]
20. Sola-Caraballo, J.; Rincón-Calderón, J.M.; Rivera-Gómez, C.; López-Martínez, J.A.; Galán-Marín, C. On-Site Risk Assessment Methodology of Historic Timber Structures: The Case Study of Santa Cruz Church. *Buildings* **2022**, *12*, 935. [CrossRef]
21. Zhang, L.; Tiemann, A.; Zhang, T.; Gauthier, T.; Hsu, K.; Mahamid, M.; Moniruzzaman, P.K.; Ozevin, D. Nondestructive assessment of cross-laminated timber using non-contact transverse vibration and ultrasonic testing. *Eur. J. Wood Prod.* **2021**, *79*, 335–347. [CrossRef]
22. Jaskowska-Lemańska, J.; Przesmycka, E. Semi-Destructive and Non-Destructive Tests of Timber Structure of Various Moisture Contents. *Materials* **2021**, *14*, 96. [CrossRef] [PubMed]
23. Yu, T.; Sousa, H.S.; Branco, J.M. Combination of non-destructive tests for assessing decay in existing timber elements. *Nondestruct. Test. Eval.* **2020**, *35*, 29–47. [CrossRef]
24. Bandara, S.; Rajeev, P.; Gad, E.; Sriskantharajah, B.; Flatley, I. Damage detection of in service timber poles using Hilbert-Huang transform. *NDT E Int.* **2019**, *107*, 102141. [CrossRef]
25. Brischke, C.; Meyer-Veltrup, L.; Bornemann, T. Moisture performance and durability of wooden façades and decking during six years of outdoor exposure. *J. Build. Eng.* **2017**, *13*, 207–215. [CrossRef]
26. Aydın, M.; Aydın, T.Y. Moisture dependent elastic properties of naturally aged black pine wood. *Constr. Build. Mater.* **2020**, *262*, 120752. [CrossRef]
27. Ingebretsen, S.B.; Andenæs, E.; Gullbrekken, L.; Kvande, T. Microclimate and Mould Growth Potential of Air Cavities in Ventilated Wooden Façade and Roof Systems—Case Studies from Norway. *Buildings* **2022**, *12*, 1739. [CrossRef]

28. Schiere, M.; Franke, B.; Franke, S.; Müller, A. Comparison between Predicted and Measured Moisture Content and Climate in 12 Monitored Timber Structures in Switzerland. *Buildings* **2021**, *11*, 181. [CrossRef]
29. Ryan, P.C.; Stewar, M.G.; Spence, N.; Li, Y. Reliability assessment of power pole infrastructure incorporating deterioration and network maintenance. *Reliab. Eng. Syst. Saf.* **2014**, *132*, 261–273. [CrossRef]
30. Niu, K.; Song, K. Hot waxing treatment improves the aging resistance of wood surface under UV radiation and water. *Prog. Org. Coat.* **2021**, *161*, 106468. [CrossRef]
31. Dietsch, P.; Kreuzinger, H. Guideline on the assessment of timber structures: Summary. *Eng. Struct.* **2011**, *33*, 2983–2986. [CrossRef]
32. Machado, J. *Conhecer a Madeira Como Base de Suporte a Ações de Reabilitação. Seminário Intervir em Construções Existentes de Madeira*; Guimarães Universidade do Minho, Escola de Engenharia (UM): Guimarães, Portugal, 2014; pp. 23–36. (In Portuguese)
33. Degl'Innocenti, M.; Nocetti, M.; Kovačević, V.C.; Aminti, G.; Betti, M.; Lauriola, M.P.; Brunetti, M. Evaluation of the mechanical contribution of wood degraded by insects in old timber beams through analytical calculations and experimental tests. *Constr. Build. Mater.* **2022**, *339*, 127653. [CrossRef]
34. Martins, S. Estruturas de Madeira—Inspecção e Diagnóstico: Aplicação em Caso de Estudo. Master's Thesis, Universidade do Minho, Guimarães, Portugal, 2009. (In Portuguese)
35. Marais, B.N.; Brischke, C.; Militz, H. Wood durability in terrestrial and aquatic environments—A review of biotic and abiotic influence factors. *Wood Mater. Sci. Eng.* **2022**, *17*, 82–105. [CrossRef]
36. Araújo, D. Avaliação de Estruturas de Madeira em Serviço—Caso de Estudo da Ermida da Ascensão de Cristo. Master's Thesis, ISEL, Lisbon, Portugal, 2015. Available online: https://repositorio.ipl.pt/bitstream/10400.21/6156/1/Disserta%c3%a7%c3%a3o.pdf (accessed on 2 August 2022). (In Portuguese)
37. Salman, A.M.; Li, Y.; Bastidas-Arteaga, E. Maintenance optimization for power distribution systems subjected to hurricane hazard, timber decay and climate change. *Reliab. Eng. Syst. Saf.* **2017**, *168*, 136–149. [CrossRef]
38. Schwartz, Y.; Raslan, R.; Korolija, I.; Mumovic, D. A decision support tool for building design: An integrated generative design, optimisation and life cycle performance approach. *Int. J. Archit. Comput.* **2021**, *19*, 401–430. [CrossRef]
39. Kaziolas, D.; Bekas, G.; Zygomalas, I.; Stavroulakis, G. Life Cycle Analysis and Optimization of a Timber Building. *Energy Procedia* **2015**, *83*, 41–49. [CrossRef]
40. Rahiddin, R.N.N.; Hashim, U.R.; Ismail, N.H.; Slahuddin, L.; Choon, N.H.; Zabri, S.N. Classification of wood defect images using local binary pattern variants. *Int. J. Adv. Intell. Inform.* **2020**, *6*, 36–45. [CrossRef]
41. Yang, G.; Liu, K.; Zhang, J.; Zhao, B.; Zhao, Z.; Chen, X.; Chen, B.M. Datasets and processing methods for boosting visual inspection of civil infrastructure: A comprehensive review and algorithm comparison for crack classification, segmentation, and detection. *Constr. Build. Mater.* **2022**, *356*, 129226. [CrossRef]
42. Califano, A.; Baiesi, M.; Bertolin, C. Novel risk assessment tools for the climate-induced mechanical decay of wooden structures: Empirical and machine learning approaches. *Forces Mech.* **2022**, *7*, 100094. [CrossRef]
43. Hosseini, S.M.; Peer, A. Wood Products Manufacturing Optimization: A Survey. *IEEE Access* **2022**, *10*, 121653–121683. [CrossRef]
44. Chen, K.; Reichard, G.; Xu, X.; Akanmu, A. Automated crack segmentation in close-range building façade inspection images using deep learning techniques. *J. Build. Eng.* **2021**, *43*, 102913. [CrossRef]
45. Rahiddin, R.N.N.; Hashim, U.R.; Salahuddin, L.; Kanchymalay, K.; Wibawa, A.P.; Chun, T.H. Local Texture Representation for Timber Defect Recognition based on Variation of LBP. *Int. J. Adv. Comput. Sci. Appl.* **2022**, *13*, 443–448. [CrossRef]
46. Instituto de Conservação da Natureza e Florestas. Available online: http://www2.icnf.pt/portal/florestas/gf/ps/rp/pinus-sylvestris (accessed on 2 August 2022).
47. Globaldis. Available online: https://www.globaldis.pt/files/files/catalog/vicaima-casquinha_vermelha_1.pdf (accessed on 2 August 2022).
48. Somapil. Available online: http://www.somapil.com/pt/madeiras/europa/casquinha-vermelha (accessed on 2 August 2022).
49. Gomes, J. Estudo da Inflamabilidade de Madeiras para Construção Usadas na Envolvente de Edifícios. Master's Dissertation, Faculdade de Ciências e Tecnologia, Universidade de Coimbra, Coimbra, Portugal, 2014. Available online: http://hdl.handle.net/10316/38836 (accessed on 27 July 2022). (In Portuguese)
50. *NP EN 335-1*; Durabilidade da Madeira e de Produtos Derivados da Madeira: Definição das Classes de Risco: Parte 1: Generalidades/Instituto Português da Qualidade; elab. CT 14 (IPQ). IPQ: Caparica, Portugal, 2018. (In Portuguese)
51. IPMA. Normal Climatological of Viana do Castelo/Meadela 1981–2010. Available online: https://www.ipma.pt/bin/file.data/climate-normal/cn_81-10_VIANA_CASTELO.pdf (accessed on 27 July 2022).
52. Branco, J.; Sousa, H. *Métodos de Inspeção e Classificação Visual de Elementos de Madeira—Manual de Curso*; Escola de Engenharia, Universidade do Minho: Guimarães, Portugal, 2014. (In Portuguese)
53. Klüppel, A.; Mai, C. Effect of seawater wetting on the weathering of wood. *Eur. J. Wood Prod.* **2018**, *76*, 1029–1035. [CrossRef]
54. Broadbent, A.D. A critical review of the development of the CIE1931 RGB color-matching functions. *Color ResAppl.* **2004**, *29*, 267–272. [CrossRef]
55. Zakaria, N.; Hammad, I.; Aly, Y. Effect of pattern materials and fabrication techniques on the color of a pressed lithium disilicate ceramic: An in vitro study. *J. Prosthet. Dent.* **2023**, *129*, 650.e1–650.e7. [CrossRef]

56. Huang, H.; Long, R.; Tong, S.H.; Cao, Y.Z.; Yuan, L.L.; Zhou, H. Cement pastes in tertiary colours: A digital approach for colouration of cement-based materials. *Constr. Build. Mater.* **2023**, *382*, 131354. [CrossRef]
57. Hernández Salueña, B.; Sáenz Gamasa, C.; Diñeiro Rubial, J.; Alberdi Odriozola, C. CIELAB color paths during meat shelf life. *Meat Sci.* **2019**, *157*, 107889. [CrossRef]