Materiales de Construcción
Vol. 68, Issue 329, January–March 2018, e149
ISSN-L: 0465–2746
https://doi.org/10.3989/mc.2018.01817

Defect characterization, diagnosis and repair of wood flooring based on a field survey

A. Delgado[a], C. Pereira[b,]✉, J. de Brito[b], J. D. Silvestre[b]

a. Instituto Superior Técnico (IST) - Universidade de Lisboa, (Lisbon, Portugal)
b. CERIS-ICIST, Dept. of Civil Engineering, Architecture and Georresources, Instituto Superior Técnico (IST) - Universidade de Lisboa, (Lisbon, Portugal)
✉clareira@sapo.pt

Received 8 February 2017
Accepted 27 June 2017
Available on line 2 March 2018

ABSTRACT: A statistical characterization of defects in 35 buildings and 98 wood floorings (softwood and hardwood floors, and laminated and engineered wood floors), their diagnostic methods and repair solutions is presented. An expert system for inspecting wood flooring, comprising the classification of defects, their most probable causes, diagnostic methods and repair techniques, was used. Results include age, affected area, severity and frequency of defects and their main causes, as well as appropriate diagnostic methods, preventive and curative repair solutions most prescribed and the most significant correlations. Scratches were detected in more than five sixths of the sample, highly associated with exterior mechanical actions, and with an inadequate finishing layer. Wearing of the finishing layer was detected in a quarter of the inspected floorings. Accordingly, the application of a suitable finishing layer and, alternatively, its replacement are the most prescribed repair techniques.

Keywords: Wood; Weathering; Decay; Durability; Characterization.

Citation/Citar como: Delgado, A.; Pereira, C.; de Brito, J.; Silvestre, J.D. (2018) Defect characterization, diagnosis and repair of wood flooring based on a field survey. Mater. Construcc. 69 [329], e149 https://doi.org/10.3989/mc.2018.01817

RESUMEN: *Caracterización de defectos, diagnóstico y reparación de suelos de madera basado en un estudio de campo.* Se presenta una caracterización estadística de defectos en 35 edificios y 98 suelos de madera (suelos de madera conífera y frondosa, pisos de madera laminada e de ingeniería de la madera), sus métodos de diagnóstico y soluciones de reparación. Se utilizó un sistema experto para inspeccionar suelos de madera, que incluía la clasificación de defectos, sus causas más probables, métodos de diagnóstico y técnicas de reparación. Los resultados incluyen edad, área afectada, gravedad y frecuencia de los defectos y sus principales causas, así como los métodos de diagnósticos apropiados, soluciones de reparación preventiva y curativa más prescritas y las correlaciones más significativas. Se detectaron arañazos en más de cinco sextos de la muestra, muy asociados con acciones mecánicas exteriores y con una capa de acabado inadecuada. El desgaste de la capa de acabado se detectó en un cuarto de los suelos inspeccionados. Por consiguiente, la aplicación de una capa de acabado adecuado y, en su caso, su sustitución son las técnicas de reparación más prescritas.

Palabras clave: Madera; Envejecimiento; Deterioro; Durabilidad; Caracterización.

ORCID ID: A. Delgado (http://orcid.org/0000-0002-0994-8979); C. Pereira (http://orcid.org/0000-0002-9535-1844); J, de Brito (http://orcid.org/0000-0001-6766-2736); J.D. Silvestre (http://orcid.org/0000-0002-3330-2000)

1. INTRODUCTION

Wood floorings are a long-established flooring solution in every continent. Wood flooring (WF) comprises both solid wood and composite wood solutions. WF is known for its easy maintenance, durability, low cost, quality control of the production process and good environmental performance (1). Functionally, wood floorings comply with today's comfort, habitability and aesthetic requirements, and additionally are quick to install.

The characteristics of the substrate, the hygrothermal conditions and the availability of skilled labor are determining factors during the installation of WF and influence their performance over time, both in indoor and outdoor areas. Defects occurrence and the degradation level of WF are highly dependent on these early-stage factors, which may lead to repairs and/or refurbishment before time. With a system that impartially identifies, records, and classifies defects in WF and their causes, the task would be easier. Prescribing the most appropriate diagnostic methods and repair solutions to eliminate the defects and corresponding causes is another useful asset of the system (2). The work of Delgado *et al.* (1) proposes such an inspection system for WF, based on a methodology also tested on gypsum plasterboard walls (3), gypsum plasters (4), renderings (5), ceramic tiling (6), natural stone cladding (7), external thermal insulation composite systems (8), flat roof waterproofing systems (9), pitched roof claddings (10), industrial floor coatings (11), architectural concrete surfaces (12), and door and window frames (13). This methodology was adapted to the specific WF technology and the study of floorings' pathological processes. To the best of the authors' knowledge, it remains the only such system in the literature.

Delgado *et al.* (1) describe in detail this WF inspection system. This paper presents a detailed statistical analysis of the results of the inspection program that validated the WF inspection system. It is a systematic approach to defect, causes, diagnostic methods and repair solutions, based on a set of 98 WF case studies, similar to the analysis of Gaião *et al.* (14).

2. INSPECTION PROGRAM

An inspection campaign was planned for buildings with defects in WF, including the pathological characterization of 98 WF representative case studies, analyzing the most suitable diagnostic and repair methods available for each specific circumstance. This field work made it possible to validate the expert system proposed for WF and its procedures, such as the defect classification system, defect rating, classification of probable causes, classification of diagnostic methods and classification of repair techniques.

The inspected WF included softwood and hardwood floors, and laminated and engineered wood floors. Nevertheless, in the statistical survey the type of flooring was not considered, as the sample was not varied enough. It is focused mainly on cork tiles and traditional timber tiles. The inspected buildings were intended to be representative of the potential market for future inspections and rehabilitation. The standard inspections consisted mainly of a visual observation of the WF, which was documented through a standard inspection and validation file. Furthermore, *in situ* tests were recommended for each defect.

All the buildings are located in the center-south region of Portugal, and 48% are in Lisbon. As for the distribution of the age of the buildings in the sample, most buildings had been built in the previous five years (37%), followed by buildings 5 to 20 years old (26%), and buildings at least 100 years old (17%). Buildings 50 to 100 years old represent 11% of the sample, while only 9% of the buildings were 20 to 50 years old. The sample of 98 WF comprised 35 different buildings. The most significant part of the inspected WF was in commercial buildings (30%), heritage buildings (29%) and residential buildings (19%). Heritage buildings are those considered historical heritage, functioning as public or cultural buildings, as opposed to ordinary buildings. Figure 1 shows that heritage buildings have a higher ratio of defects per pavement. For every building each continuous WF was described in an inspection file.

2.1. Inspection and validation files

The inspection files contain all relevant information on the buildings and WF, so that different inspections can be compared. An inspection file was filled

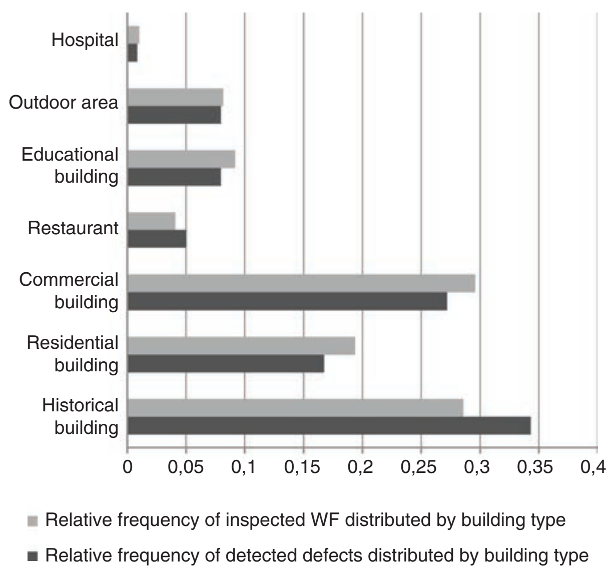


FIGURE 1. WF and detected defects distributed according to building type in the sample

describing each inspected WF. First, the building location, use, construction date, area, percentage of wood floor covering, constructive typology, and any contact information are indicated. Next, all the wood floorings are described stating the installation date, detailed constructive characterization, type of cleaning undertaken, and relevant location specific data.

While the inspection file allows a constructive characterization of the building and of each inspected WF, the validation file provides information on the detected pathological phenomena, for statistical purposes. One validation file was filled for each WF, identifying and recording the main WF defects detected. These records were then used to validate the inspection system, namely the classification of defects, causes, diagnostic methods and repair techniques, as well as the correlation matrices between these parameters. Each validation file identifies: the kind of defects found, location and size of every defect, conditions for the defect to progress, substrate cracking, evidences of expansion of the parts, aesthetical value of the affected area and severity level, probable causes, diagnostic methods proposed, and repair techniques proposed. The content of the inspection and validation files is fully described by Delgado *et al.* (1). The discussion of the data in the inspection and validation files is the basis of the present statistical analysis.

2.2. Diagnosis and statistical characterization of WF pathology

The WF inspection system includes a classification system for defects in WF and their direct and indirect causes (1). The system groups defects (D) according to location on the surface (S) of the WF or in joints and interfaces (JI), within the WF, or between the WF and other floor coverings or protruding elements. In total, 16 types of defects were defined, according to scientific references (15–22). Defects are coded with a D for defect, hyphen and the group reference, namely S for surface, and JI for joints and interfaces, followed by sequential numbering. D-S group defects are then divided into two subgroups: aesthetic defects (D.1-S) and functional defects (D.2-S). Probable causes, diagnostic methods and repair techniques are coded using a similar method (1).

The inspection system considers 38 probable causes of WF defects, which were classified in chronological order, according to the following groups: production errors (C-A), design errors (C-B), execution errors (C-C), exterior mechanical actions (C-D), biological actions (C-E), environmental actions (C-F), and maintenance errors (C-G).

For each detected defect, further diagnostic methods were recommended from a set of 11 proposed appropriate methods. These methods were divided in four groups. Three are nondestructive tests (T-ND): T.1-ND Aided visual observation, T.2-ND Traditional nondestructive tests and T.3-ND Nontraditional nondestructive tests. The fourth group is T-D Destructive tests.

The inspection system, presented by Delgado *et al.* (1), also associates a set of 18 preventive (RP) and curative (RC) repair techniques with the defects. These two main groups of repair techniques were divided in four subgroups corresponding to intervention in WF covering (RP-A and RC-A), WF surface (RP-B and RC-B), WF substrate (RP-C and RC-C) or in joints between pieces of WF or with protruding elements (RP-D and RC-D).

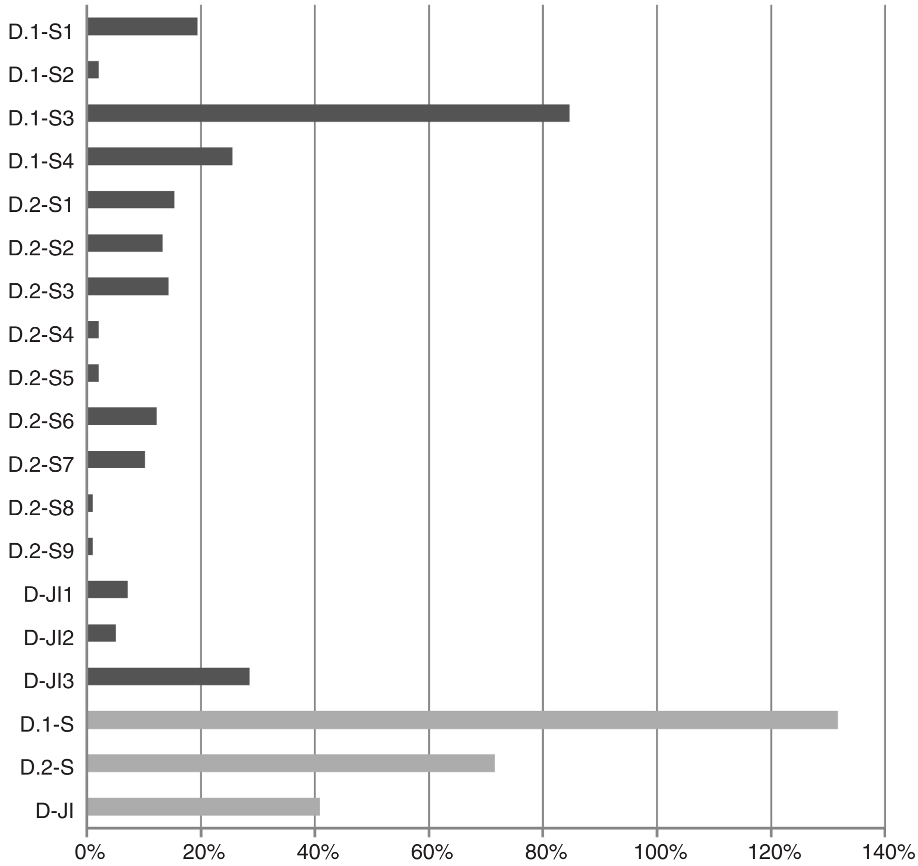
3. RESULTS AND DISCUSSION

3.1. Defects observed in the sample

In all, 239 defects were detected in the sample of 98 WFs (only one event per defect type was recorded for each WF), resulting on average in 2.44 defects per pavement. Figure 2 shows the relative frequency of detected defects (number of records divided by 98, the number of inspected WF). Defects are described in detail by Delgado *et al.* (1). D.1-S3 Scratches or wrinkles (84.7%) was by far the most common defect detected in the sample. According to Baar *et al.* (23), the occurrence of scratches on the wood surface protection layer may influence the susceptibility of wood to the occurrence of other defects, when exposed to water. Hence, the incidence of scratches in this sample may be significant in terms of degradation modelling. D.1-S3 was followed by D-JI3 Change of joint size (28.6%) and D.1-S4 Wearing or detachment of the finishing layer (25.5%). Considering some defect classification differences, the results on Neto and de Brito's (24) color change defects, referring to natural stone claddings, are similar to those on WF, as D.1-S1 Staining or color change and D.1-S2 Cigarette marks represent about 21% of the sample, while Neto and de Brito's (24) color change defects represent about 27% of all defects. However, in Neto and de Brito's (24) sample, joint defects were as relevant as color change defects (28% of all defects), while in WF all D-JI Joints and interfaces defects represent about 41% of the sample. This is a sign of the vulnerability of joints in WF, as they are subject to variations in wood moisture content and, consequently, to size variations according to climate changes, as verified by the high frequency of the defect D-JI3 Change of joint size in WF.

Five of the defect types were only detected up to two times, namely D.1-S2 Cigarette marks, D.2-S4 Detachment of elements from substrate, D.2-S5 Rot, D.2-S8 Delamination and D.2-S9 Crumbling. Nevertheless, these defects were kept in the analysis.

These general results, specifically on WF, differ from those of Chong and Low (25), referring



D.1-S1 Staining or color change, **D.1-S2** Cigarette marks, **D.1-S3** Scratches or wrinkles, **D.1-S4** Wearing or detachment of the finishing layer, **D.2-S1** Warping, swelling, or other flatness deficiencies, **D.2-S2** Cracking of elements and/or joints (possibly from substrate cracking), **D.2-S3** Broken or splintered elements, **D.2-S4** Detachment of elements from substrate, **D.2-S5** Rot, **D.2-S6** Moisture, **D.2-S7** Xylophage attack, **D.2-S8** Delamination, **D.2-S9** Crumbling, **D-JI1** Color change, **D-J12** Detachment or loosening of mass of joint material, **D-J13** Change of joint size. **D.1-S** Surface aesthetic defects, **D.2-S** Surface functional defects, **D-JI** Joints and interfaces defects.

FIGURE 2. Relative frequency of the occurrence of defects and groups of defects in the 98 inspected wood floorings

to general floors defects. In that sample, the most frequent defects found in floorings under use were cracks, water seepage and delaminated tiles.

Considering the groups of defects, aesthetic defects (D.1-S) are the kind of defects most frequently detected: on average each pavement had 1.4 aesthetic defects.

Figure 3 shows the relationship between the average number of defects of each type and the age of the pavement it was detected in. Defect D.1-S3 Scratches or wrinkles, as the most frequent defect, has the highest average number of defects in WF of every age. Contrary to expectations, older buildings in this sample do not show greater frequency of this anomaly than the others, probably due to the type of solution, materials used and previous repairs. Defects D.1-S3 represent an average of 1.02 defects in buildings 20 to 50 years old, showing lack of maintenance. As for other defects, D.2-S7 Xylophage attack is the defect most related with the age of the WF, as an average of 0.55 defects occur in WF more than 100 years old. Although some of the inspected floorings had possibly undergone repair operations to eliminate previous xylophage attacks, it is significant that one in every two floorings more than 100 years old shows this type of defect, even if on a limited area, requiring immediate action. Despite these results, it is important to highlight that, in the whole sample, defects D.2-S5 Rot, D.2-S6 Moisture and D.2-S7 Xylophage attack were not representative. As general literature usually refers to mould, fungi and insects as the main origin of defects on wood (26), it is relevant that the

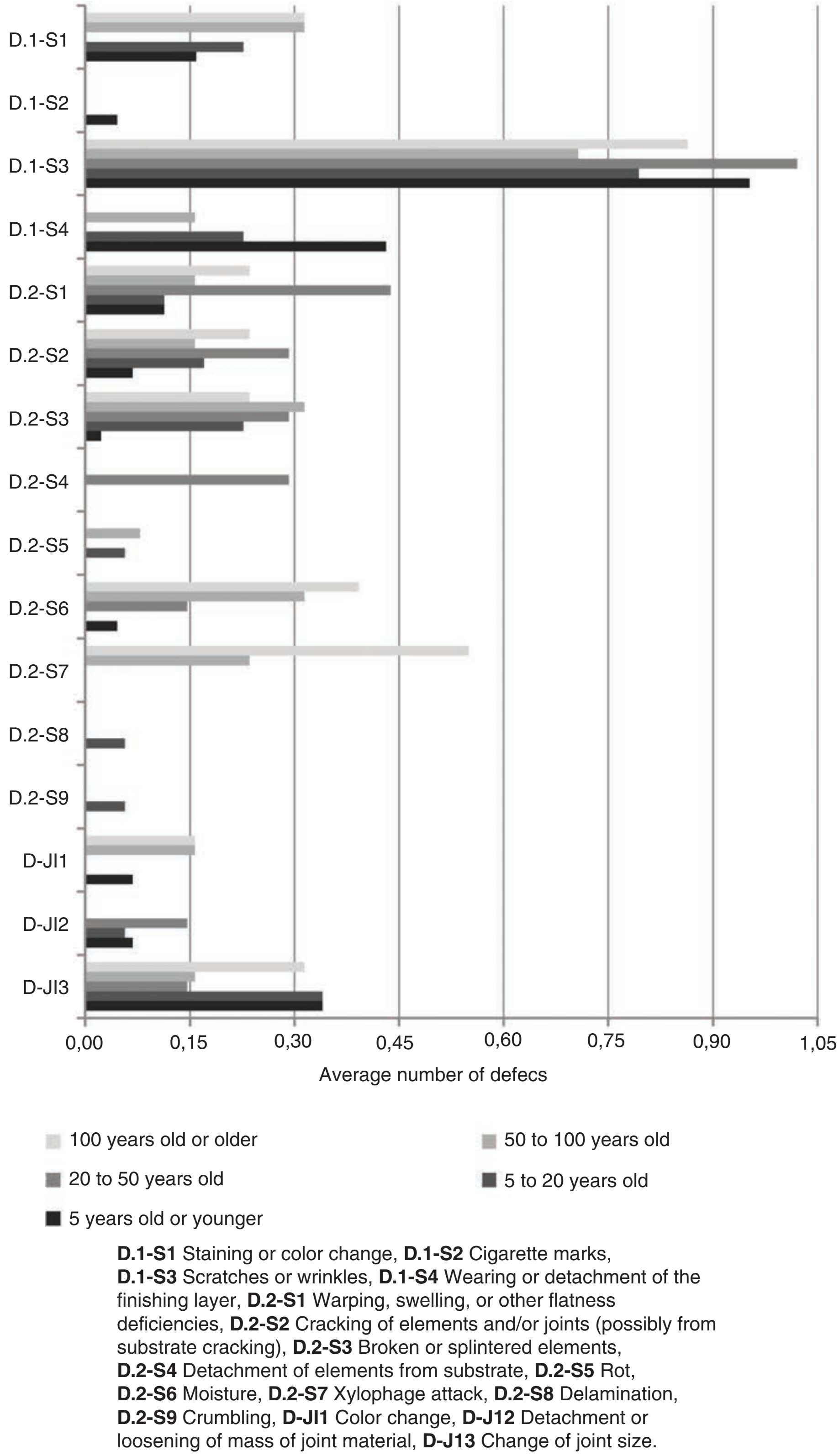


FIGURE 3. Average number of defects per inspected flooring, according to the age of the flooring

inspected WF were not substantially affected by the effects of these organisms, whether or not they had already been subject to repairs. Buildings less than 5 years old have greater incidence of defect D.1-S4 Wearing or detachment of the finishing layer, which may show that the choice of materials was not adequate to use conditions. According to the results obtained, age does not appear to be a determining factor for the occurrence of defects, which contradicts the 42 years of estimated service life of hardwood floors calculated by Minne and Crittenden (27). The maintenance that WF are subjected to seems to play a more relevant role than age.

Every defect was rated in terms of repair urgency (1):

- 0 = Action required immediately or in the short-term (6 months);
- 1 = Action required in the medium-term (12 months); or
- 2 = Action required in the long-term (reassessment at the next routine inspection).

Repair urgency depends on the severity of the defect when it is detected. For each defect the criteria to rate its repair urgency were clearly defined, supporting the inspection file. For example, the defect file for D.2-S4 Detachment of elements from substrate indicates that this defect is classified by the percentage of affected area and by the aesthetic value of the affected area (high, medium or low). When this defect is detected, if users' safety is compromised, or if the affected area is over 5%, then the repair urgency level is 0. If the defect presents progression features, the repair urgency level is 1. For the remaining instances of D.2-S4 defect, the repair urgency level is 2.

The commonest repair urgency level is "1" (42%) and the highest severity level (0) represents 23% of the sample. Observing Figure 4, a repair

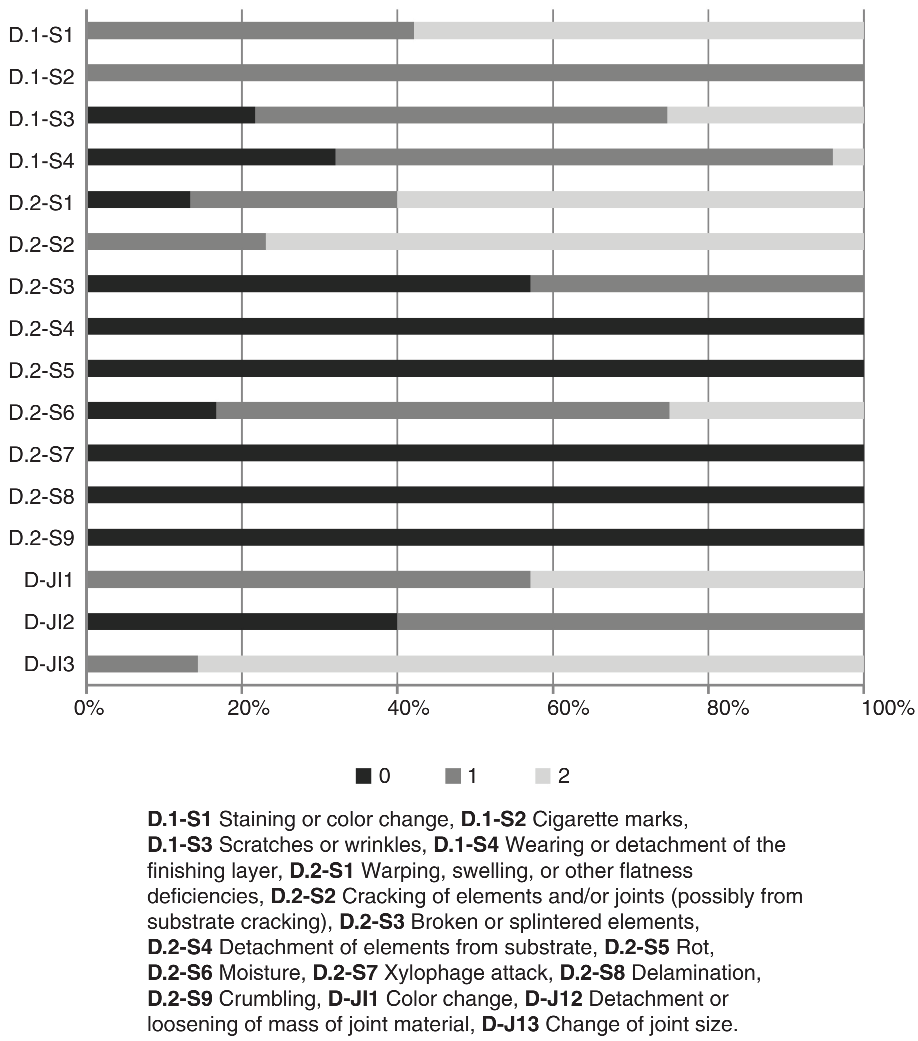
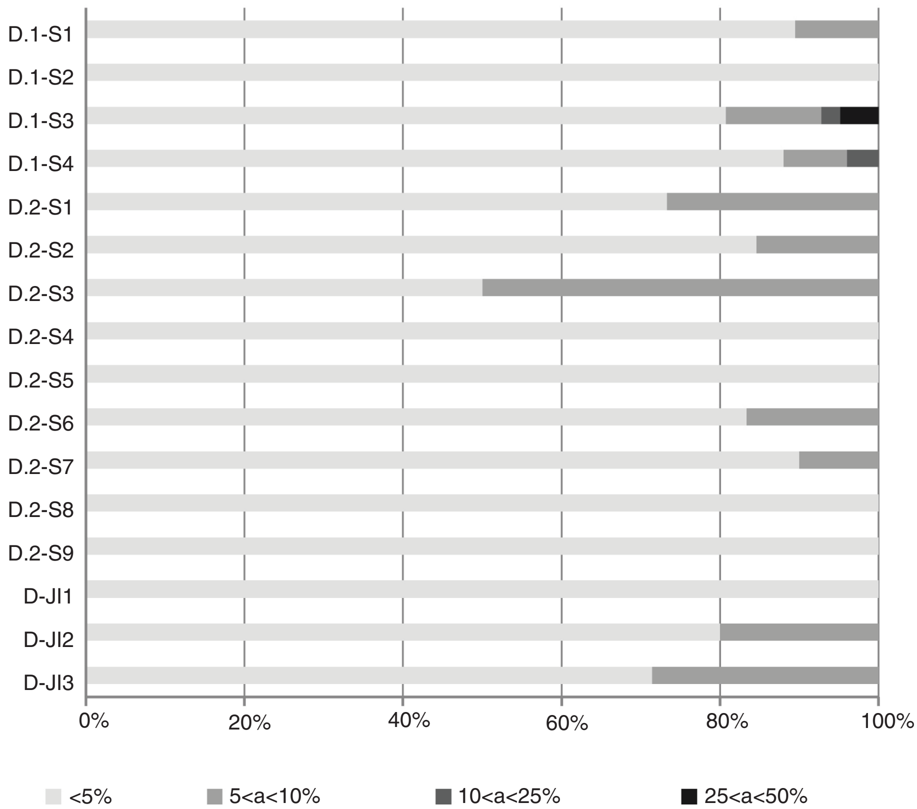


FIGURE 4. Relative frequency of the repair urgency level per type of defect in the sample

urgency per defect analysis leads to different conclusions. Defects D.2-S3 Broken or splintered elements, D.2-S4 Detachment of elements from substrate, D.2-S5 Rot, D.2-S7 Xylophage attack, D.2-S8 Delamination, D.2-S9 Crumbling and D-JI2 Detachment or loosening of mass of joint material have the highest repair urgency (0) in more than 33% of the sample. They can all compromise the flooring's integrity, even D-JI2, whose urgency levels reveal how important joint maintenance is to extend the WF's service life. Considering that D.2-S3 and D.2-S7 affect a wider sample (14 and 10 defects respectively), their urgency frequency may be more significant. Although aesthetical defects require less demanding works, and do not compromise the flooring's integrity, they should not be less considered, especially according to the flooring's function.

As for the area of flooring affected by each defect, Figure 5 shows the data registered at the inspections. Defect D.1-S3 Scratches or wrinkles, which is the one that affects the widest sample (83 defects), is also the one with the widest affected areas, since in 5% of the cases the D.1-S3 defects affect 25% to 50% of the WF's area. In the sample, defect D.2-S3 Broken or splintered elements affects a large flooring area (from 5% to 10%) in 50% of the cases. Comparing these results with those on natural stone floorings (24), some differences are observed. In natural stone floorings, color changes are the type of defect that affects wider areas, while in WF, the corresponding defects (D.1-S1 Staining or color change and D.1-S2 Cigarette marks) mainly affect areas of less than 5% of the flooring. Neto and de Brito (24) attributed this result to infrequent cleaning, but that may not be the case in WF, as staining is most probably associated with humidity or fungi.



D.1-S1 Staining or color change, **D.1-S2** Cigarette marks, **D.1-S3** Scratches or wrinkles, **D.1-S4** Wearing or detachment of the finishing layer, **D.2-S1** Warping, swelling, or other flatness deficiencies, **D.2-S2** Cracking of elements and/or joints (possibly from substrate cracking), **D.2-S3** Broken or splintered elements, **D.2-S4** Detachment of elements from substrate, **D.2-S5** Rot, **D.2-S6** Moisture, **D.2-S7** Xylophage attack, **D.2-S8** Delamination, **D.2-S9** Crumbling, **D-JI1** Color change, **D-J12** Detachment or loosening of mass of joint material, **D-J13** Change of joint size.

FIGURE 5. Relative frequency of the affected area per type of defect in the sample

3.2. Direct or indirect probable causes of defects

In total, 1319 probable causes (of 38 different types) were identified in the inspection campaign, as direct, or close, causes, or as indirect, or initial, causes (1). Therefore, an average of 5.5 probable causes were assigned to each recorded defect. It must be noted that no *in situ* or laboratory tests were actually performed, as inspections consisted solely on visual observation. So, the registered probable causes point out several possibilities.

C-D Exterior mechanical actions account for 32% of the causes in the sample, followed by C-C Execution errors, which represent 25% of the sample. It is important to disseminate detailed information on WF construction systems, so that solutions are chosen according to the use of the floor, as well as to improve the selection of techniques and installation materials. Exterior mechanical actions are not accounted for in the Chong and Low's (25) study, but poor workmanship is also a relevant cause for flooring defects. It is responsible for 35% of defects in floorings under use.

As each defect is confronted with the groups of probable indirect causes, some issues become evident. Figure 6 (left) shows that 76% of aesthetic defects (D.1-S) were indirectly caused by exterior mechanical actions (C-D). Aesthetic defects are also highly associated (56%) with execution errors (C-C). Aesthetic defects area not indirectly caused by any production errors. As for functional defects (D.2-S), 52% of defects are indirectly caused by one environmental action (C-F) and 48% by maintenance errors (C-G). 18% of defects on joints and interfaces (D-JI) are indirectly caused by at least one execution error (C-C).

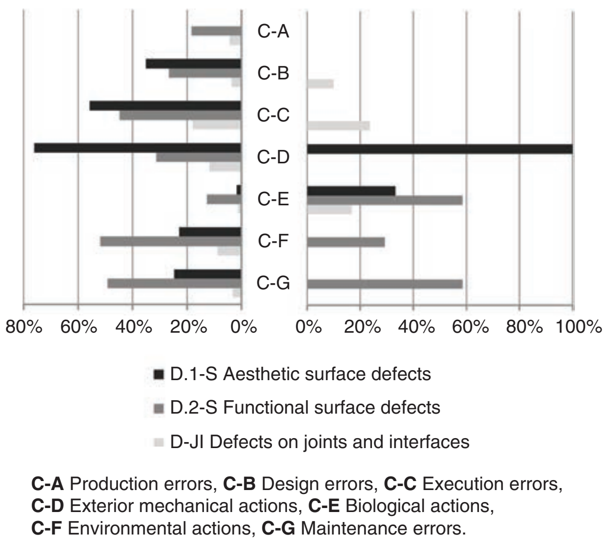


FIGURE 6. Relative frequency of the groups of probable causes, according to groups of defects they were attributed to, considering indirect causes on the left and direct causes on the right

Observing Figure 6 (right), it is interesting to notice that all aesthetic defects (D.1-S) are directly caused by at least one exterior mechanical action (C-D). Biological direct causes (C-E) are also moderately associated with aesthetic defects (33%). As for functional defects (D.2-S), 59% of these kind of defects are directly caused by biological actions (C-E), the same amount of functional defects (D.2-S) directly associated with maintenance errors (C-G). Defects on joints and interfaces (D-JI) are directly associated with execution errors (C-C) in 24% of the D-JI defects registered.

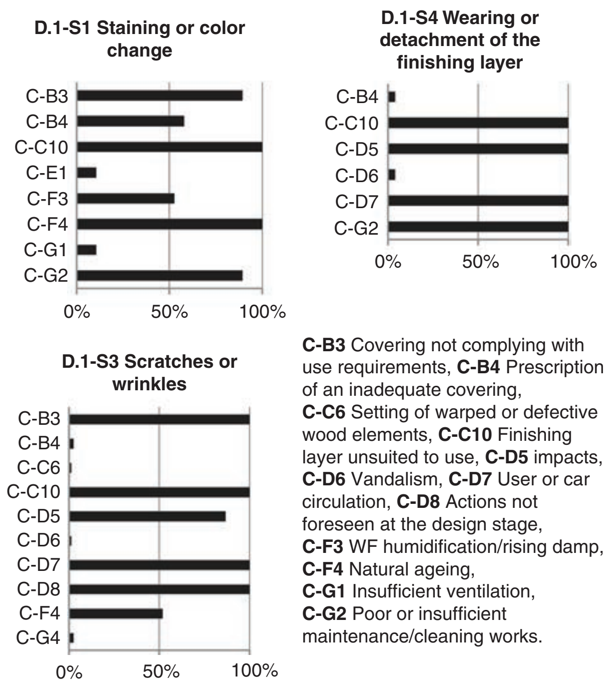
Production errors (C-A) are not directly associated with any specific defect. On the one hand, design errors (C-B) and execution errors (C-C) are only relevant for D-JI defects. On the other hand, environmental actions (C-F) and maintenance errors (C-G) are only directly associated with functional defects (D.2-S).

Additionally, the results reveal other features. Aesthetic defects (D.1-S) are not associated with production errors. Execution errors (C-C) are the main contributors to the occurrence of D.1-S Aesthetic defects (100%), but C-D Exterior mechanical actions (85%) and C-B Design errors (79%) also play a main role. Functional defects (D.2-S) are evenly associated with C-B Design errors (61%) and C-F Environmental actions (60%). As for D-JI Defects on joints and interfaces, there are four groups of causes that stand out, as their association with these group of defects is above 70%, namely C-D Exterior mechanical actions, C-C Execution errors, C-B Design errors and C-A Production errors. C-E Biological actions are the group of causes less associated with WF defects in this sample.

3.3. Probable causes contribution to each defect

To understand the contribution of each individual cause to the occurrence of each defect, it is important to analyze them individually. For this analysis, only defects that were observed more than 10 times were considered. Causes that were observed at least once for each defect were considered. Considering these criteria, only D.1-S1 Staining or color change, D.1-S3 Scratches or wrinkles, D.1-S4 Wearing or detachment of the finishing layer, D.2-S1 Warping, swelling, or other flatness deficiencies, D.2-S2 Cracking of elements and/or joints (possibly form substrate cracking), D.2-S3 Broken or splintered elements, D.2-S6 Moisture and D-JI3 Change of joint size are analyzed in detail.

Figure 7 shows the data on causes probably associated with defect D.1-S1 Staining or color change. This defect was identified 19 times, to which 5.2 probable direct and indirect causes were attributed on average. All these defects can be associated with



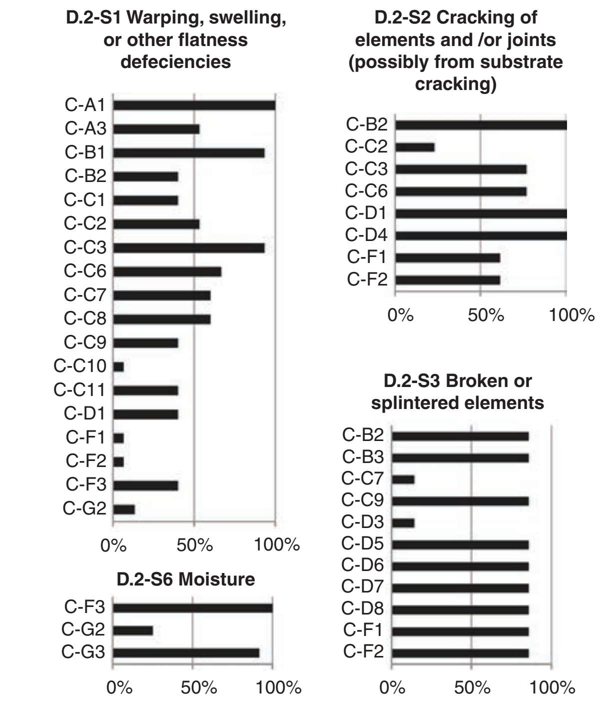
C-B3 Covering not complying with use requirements, **C-B4** Prescription of an inadequate covering, **C-C6** Setting of warped or defective wood elements, **C-C10** Finishing layer unsuited to use, **C-D5** impacts, **C-D6** Vandalism, **C-D7** User or car circulation, **C-D8** Actions not foreseen at the design stage, **C-F3** WF humidification/rising damp, **C-F4** Natural ageing, **C-G1** Insufficient ventilation, **C-G2** Poor or insufficient maintenance/cleaning works.

FIGURE 7. Contribution of probable causes to the most representative surface aesthetic defects detected: D.1-S1 (19 detected defects), D.1-S3 (83 detected defects) and D.1-S4 (25 detected defects)

a finishing layer unsuited to use (C-C10) and natural ageing (C-F4). Covering not complying with use requirements (C-B3) and poor or insufficient maintenance/cleaning works (C-G2) are associated with over 80% of these defects, leading to being considered highly probable causes. This defect is associated with causes from groups C-B, C-C, C-E, C-F and C-G. They are not related with production errors nor exterior mechanical actions.

Defect D.1-S3 Scratches or wrinkles was identified in 83 WF cases. To each an average of 5.3 probable causes (direct and indirect) were considered. All the sample was associated with a covering not complying with use requirements (C-B3), a finishing layer unsuited to use (C-C10), user or car circulation (C-D7) and with actions not foreseen at design stage (C-D8), as shown in Figure 7. Exterior mechanical actions (C-D group of causes) are highly associated with this defect.

In Figure 7, the data on causes of defect D.1-S4 Wearing or detachment of the finishing layer are also available. It was identified in 25 pavements and associated with 4.1 probable causes (direct and indirect) per defect. All these defects were associated with a finishing layer unsuited to use (C-C10), impacts (C-D5), user or car circulation (C-D7) and with poor or insufficient maintenance/cleaning works (C-G2). Once again, C-D Exterior mechanical actions are the group of probable causes most associated with this defect.



C-A1 inadequate wood drying, **C-A3** Wood cutting not following wood fiber direction, **C-B1** Wrong design joints between elements or with protruding elements, **C-B2** imadequate fixing/fastening system, **C-B3** Covering not complying with use requirements, **C-C1** Wrong interpretation of the design plans, **C-C2** Lack of support preparation before WF application, **C-C3** Use of excessively dry or wet wood, **C-C6** Setting of warped or defective wood elements, **C-C7** Voiods between wood pieces and bedding material, C-C8 Inadequate thickness of the bedding material, **C-C9** Defective nailing of wood elements on the substrate, **C-C10** Finishing layer unsuited to use, **C-C11** Deficient joint filling, **C-D1** Differential substrate-WF movements, **C-D3** Shrinkage or expansion of the bedding material, **C-D4** Initial shrinkage and/or expansion of the joint material, **C-D5** Impacts, **C-D6** Vandalism **C-D7** User or car circulation, **C-D8** Actions not foreseen at the design stage, **C-F1** Solar radiation, **C-F2** Thermal shock, **C-F3** WF humidification / rising damp. **C-G2** Poor or insufficient maintenance/cleaning works, **C-G3** Pipe ruptures near or over the WF.

FIGURE 8. Contribution of probable causes to the most representative surface functional defects detected: D.2-S1 (15 detected defects), D.2-S2 (13 detected defects), D.2-S3 (14 detected defects) and D.2-S6 (12 detected defects)

All the surface aesthetic defects (D.1-S) were associated with cause C-C10 Finishing layer unsuited to use, an execution error that reveals unfamiliarity of the project team with materials' technical features and limitations and requirements of the flooring system.

As for defect D.2-S1 Warping, swelling, or other flatness deficiencies, data on probable causes are available in Figure 8. This defect was identified in 15 of the inspected pavements, to which 7.9 direct or indirect probable causes were attributed on average. Only one probable cause is associated with all detected defects, which is inadequate wood drying (C-A1). But the wrong design of joints between elements or with protruding elements (C-B1), and the use of excessively dry or wet wood (C-C3), both associated with 93% of these defects, are also highly probable causes. Causes from the group C-C Execution errors are highly represented in this sample of defects.

Defect D.2-S2 Cracking of elements and/or joints (possibly form substrate cracking) was present in 13 of the inspected pavements. An average of 5.5 probable causes (direct or indirect) were attributed to each of these defects. As Figure 8 shows, this defect was always considered to be associated with an inadequate fixing/fastening system (C-B2), differential substrate-WF movements (C-D1) and with the initial shrinkage and/or expansion of joint material (C-D4).

In Figure 8, data on probable causes of defect D.2-S3 Broken or splintered elements are also shown. This defect was detected in 14 floors, each associated with an average of 6.1 probable causes for their occurrence. No probable direct or indirect cause is associated with all these defects, and the sample presents a set of causes with an equal contribution to its appearance. Voids between wood pieces and bedding material (C-C7) and shrinkage or expansion of bedding material (C-D3) are only sporadic causes. The main contributor is the group of causes C-D Exterior mechanical actions.

Defect D.2-S6 Moisture was identified in 12 WFs. An average of 2.2 probable causes were attributed to each. Environmental actions (C-F) and maintenance errors (C-G) generate moisture. The most significant are WF humidification/rising damp (C-F3) and pipe ruptures near or over WF (C-G3), as shown in Figure 8. Poor or insufficient maintenance/cleaning works (C-G2) are a less relevant cause.

There are 25 causes associated with more than 10% of surface functional defects (D.2-S). The cause most associated with these defects was C-B2 Inadequate fixing/fastening system, associated with 47% of defects.

Analyzing the causes for defect D-JI3 Change of joint size, it is evident in Figure 9 that causes belong to various groups of causes (C-A, C-B, C-C, C-D and C-F). The following four probable causes are associated with all these defects: inadequate wood drying (C-A1), wood cutting not following wood fiber direction (C-A3), wrong design of joints between elements or with protruding elements (C-B1), and differential substrate-WF movements (C-D1). These causes are the most representative in the whole sample of defects on joints and interfaces (D-JI). D-JI3 defect was identified in 18 pavements, with an average of 7.6 probable causes attributed to each one.

Design errors (C-B) are associated with some of the main defects found in the sample. It agrees with the results of Ishak *et al.* (28), referring to the implications of design deficiency on the building's service life. Inefficient detailing, inadequate material selection and poor design for maintenance access, along with thermal movement, were considered the main implications of design fault on building maintenance. As mentioned, inefficient detailing affects mainly D.2-S1 Warping, swelling, or other flatness deficiencies, D.2-S2 Cracking of elements and/or joints and D-JI3 Change of joint size. As for inadequate material selection, it is associated with D.1-S1 Staining or color change and D.1-S3 Scratches or wrinkles. These defects are highly frequent in the sample (D.1-S3, D-JI3 and D.1-S1), which proves the importance of careful design, considering the dire consequences.

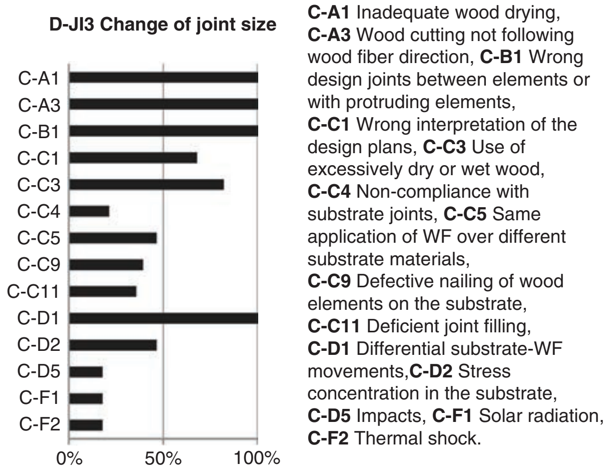
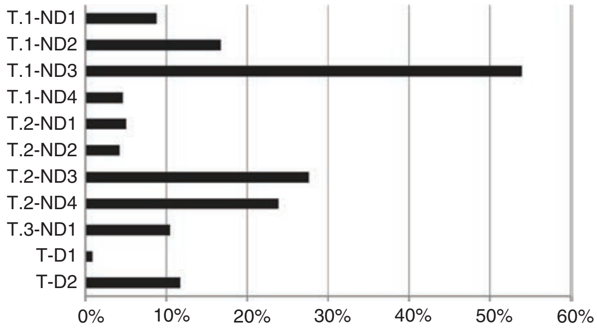


FIGURE 9. Contribution of probable causes to the 28 D-JI3 defects detected

3.4. WF diagnostic methods

The inspection system of WF includes a proposal of inspection methods to better diagnose the detected defects (1). In some cases, these methods may be useful to describe the severity, extension and evolution of defects, which otherwise could not be assessed. They may also help to confirm the causes of defects. Eleven *in situ* diagnostic methods were considered, organized in four groups. In the inspection program, for each detected defect, an average of 1.7 diagnostic methods were recommended, taking the classification list of defects into account. Only 7% of the diagnostic methods indicated correspond to destructive tests, which is an acceptable number. Non-destructive diagnostic methods are preferred as they preserve the integrity of the cladding and, generally, have a lower cost, although sometimes only qualitative results are obtained.

The most prescribed method was T.1-ND3 Evaluation of other singularities. It was recommended for more than 50% of the detected defects (Figure 10). This diagnostic method associates the analyzed defect with other defects or with temporary environmental circumstances that may help to understand the pathological phenomena. Technically and financially, T.1-ND3 is a useful low-demanding method.



T.1-ND1 Flatness evaluation, **T.1-ND2** Crack or fissure measurement, **T.1-ND3** Evaluation of other singularities, **T.1-ND4** Evaluation of biological actions, **T.2-ND1** Metal blade, **T.2-ND2** Percussion test, **T.2-ND3** Moisture measurement (surface and/or environmental), **T.2-ND4** Temperature measurement (surface and/or environmental), **T.3-ND1** Superficial hardness measurement, **T-D1** Pull-off test, **T-D2** Inner moisture measurement.

FIGURE 10. Relative frequency of the proposed diagnostic methods in the 239 detected defects

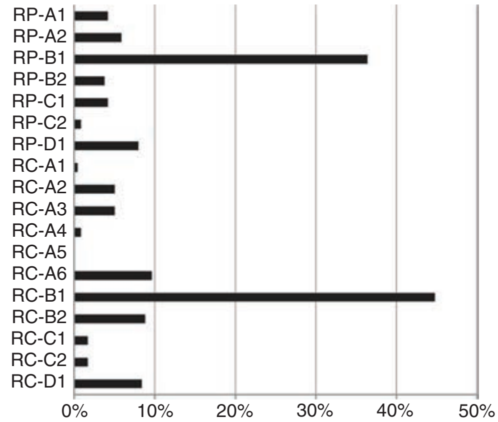
The diagnostic methods T.2-ND3 Moisture measurement (surface and/or environmental) and T.2-ND4 Temperature measurement (surface and/or environmental) were prescribed for more than 20% of the defects. As wood is a raw material sensitive to environmental conditions, it makes sense that temperature and moisture conditions are evaluated to diagnose the origin of an anomalous symptom.

3.5. WF repair techniques

For each defect identified in the inspection campaign an average of 1.5 repair techniques were prescribed. There are situations in which more than one technique is viable, the choice depending on costs and efficiency. Furthermore, the combination of repair techniques can be the best procedure in some cases, namely when preventive and curative actions should be considered. Moreover, 42% of the repair techniques were preventive (RP), i.e. they intend to eliminate the causes, and 58% were curative (RC), i.e. they intend to eliminate the defects.

Considering the sample of 98 wood floors, each floor should be subject to works considering an average of 3.6 repair techniques, since each floor presents an average of 2.44 defects. Repairs should be planned considering the floor as a whole, analyzing all defects and causes, and combining all necessary operations in a multiple-step intervention.

Observing Figure 11, there are two repair techniques that stand out. RC-B1 Removal/replacement of finishing layer was prescribed for 45% of the defects and RP-B1 Application of suitable finishing layer was prescribed for 36% of the defects. Both techniques refer to the WF surface, specifically to the finishing layer. So, as expected, in 31% of defects, both techniques were recommended, as their combination seems to be the correct approach.



RP-A1 Protection against biological agents, **RP-A2** Protection against physical-chemical agents (waterproofing and fire protection products), **RP-B1** Application of suitable finishing layer, **RP-B2** Anticorrosive protection of metallic elements, **RP-C1** Repair of defects in pipes, **RP-C2** Repair of leaking roofs and walls, **RP-D1** Repair of joint material, **RC-A1** Treatment of photodegradation, **RC-A2** Treatment of biodegradation, **RC-A3** Reinforcement with metal elements, **RC-A4** Reinforcement with composite elements, **RC-A5** Consolidation with concrete,RC-A6 Partial or total WF replacement,**RC-B1** Replacement of the finishing layer, **RC-B2** Removal/replacement of corroded metal elements, **RC-C1** Partial or total replacement of the bedding material, **RC-C2** Injection of voids with resin, **RC-D1** Partial or total replacement of the joint material.

FIGURE 11. Relative frequency of the prescribed repair techniques in the 239 detected defects

They were prescribed for all defects identified as D.1-S4 Wearing or detachment of the finishing layer, and they were also considered appropriate for 74% of D.1-S1 Staining or color change defects. RC-B1 was prescribed to 81% of D.1-S3 Scratches or wrinkles defects.

Nejad *et al.* (29) tested coated heat-treated and untreated wood samples used in flooring solutions. Scratch resistance was better in heat-treated samples, probably due to a shallow penetration of the coating, leading to a higher dry film thickness. Heat-treated coated wood samples also had a significantly lower color change after house-hold chemical tests. The application of an adequate finishing layer, combined with a proper wood treatment, may prevent scratches defects on WF, as well as stains or color changes.

As for other representative defects in the sample, RC-A6 Partial or total WF replacement and RC-C1 Partial or total replacement of bedding material were prescribed for all D.2-S4 Detachment of elements from substrate defects.

RC-A6 Partial or total WF replacement was considered suitable for all D.2-S3 Broken or splintered elements defects. Repair techniques RC-A3 Reinforcement with metal elements and RC-B2 Removal/replacement of corroded metal elements are also considered appropriate for 86% of D.2-S3 defects.

As for D.2-S6 Moisture, repair techniques RP-A2 Protection against physical-chemical agents

Table 1. Curative repair techniques adequate for defect D.2-S5 - Rot

DEFECT - REPAIR TECHNIQUES CORRELATION FILE: Defect D.2-S5	
Curative repair techniques	**Procedure**
RC-A2 treatment of biodegradation	Before any intervention, the damp source should be eliminated. 1. Superficial mould - superficial brushing and application of chemical protection agent; 2. Chromogenic mould - decrease humidity under 16% and apply a solution of chemical products via superficial pulverization in order to eliminate/reduce the unwanted color difference; 3. Rot mould - after determining the fungus type and identifying the degraded areas and corresponding severity levels, the damp source should be eliminated and the area ventilated; sanitation of wood piece and curative and preventive chemical impregnation by brushing*. For dry rot fungus, this treatment should be followed by the disinfestation of the area in a radius of two to three meters, by wood fumigation, and thermotherapy. *Brushing allows onsite treatment but it is not an efficient method, given its shallow impregnation depth. In special cases, the damaged pieces can be taken offsite to an autoclave for impregnation under vacuum and then moved back to the construction site.
RC-A4 reinforcement with composite elements	The consolidation of WF is made via the sanitation of degraded wood and its replacement by epoxide resins.
RC-A6 partial or global WF replacement	1. Removal of degraded pieces; 2. Definition of the pieces to be treated and repaired; the new wood pieces should be similar to the original ones and disinfested; 3. Removal of bedding material; 4. Replacement of bedding layer and placement of new pieces allowing for intermediate joints in the periphery of the new area. In the areas of the substrate with stress concentration, the new bedding layer should include a glass-fibre net in order to degrade the stress between the substrate and wood pieces.
RC-B1 - replacement of finishing layer	1. Removal of finishing layer; 2. Treatment of wood pieces; 3. Replacement of finishing layer with a solution suitable for final use. In order to guarantee an acceptable aesthetical appearance, the intervention should include all the room area.

(waterproofing and fire protection products) and RP-C1 Repair of defects in pipes are considered the most suitable, as they were prescribed for 75% and 83% of these defects, respectively.

An example of a relationship between defects and repair techniques in WF is shown in Table 1. This table includes the curative and preventive repair techniques that may be used in interventions in defect D.2-S5 - Rot (the techniques with a high correlation are underlined).

4. CONCLUSION

The analysis presented allowed outlining the degradation profile of a statistically significant sample of WF in existing buildings. Such an analysis is very important for suppliers, designers, installers and users, as all need to learn from previous mistakes in order to improve the construction quality of WF.

Different expert systems for the evaluation of defects in buildings already exist, but, in terms of scope and aim, no similar research work has been found in the specialized literature. Thus, the data analysis presented in this paper is innovative and robust, as it is supported by a statistically significant validation work. The inspection program included 98 wood floorings (WF) with defects, a sample diverse in age, building typology and WF system. It was essential to validate the inspection procedure and confirm the initial theoretical presuppositions, while developing the inspection and diagnosis system. It is expected that the systematic approach used in the presented inspection campaign can help future inspection procedures to be more objective and, at the same time, standardized, based on a consistent working database for the prevention and repair of similar defects.

The analysis of the collected data highlighted the most frequent defects and its causes. Scratches and wrinkles were the most detected defect, highly associated with external mechanical actions. In fact, external mechanical actions and execution errors were the main causes of detected defects. In this context, it is clear that more attention needs to be paid to a good choice of materials, namely finishes need to be adequate to use requirements and the fixing/fastening system needs to be carefully considered at an early stage. At the production phase, wood needs to be dried properly, and while in use, WF need regular specific maintenance.

Further collection of data on WF defects will enable building a wider sample and precise degradation models.

ACKNOWLEDGEMENTS

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

REFERENCES

1. Delgado, A.; de Brito, J.; Silvestre J.D. (2013) Inspection and diagnosis system for wood flooring. *J. Perform. Constr. Fac.* 27 [5], 564–574. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000342
2. Ferraz, G.T.; de Brito, J.; Freitas, V.P. de; Silvestre, J.D. (2015) Integrated technical management systems: inspection and repair of non-structural elements. *ALCONPAT Journal* 5 [2], 129–140.
3. Gaião, C.; de Brito, J.; Silvestre, J.D. (2011) Inspection and diagnosis of gypsum plasterboard walls. *J. Perform. Constr. Fac.* 25 [3], 172–180. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000149
4. Pereira, A.; Palha, F.; de Brito, J.; Silvestre, J.D. (2011) Inspection and diagnosis system for gypsum plasters in partition walls and ceilings. *Constr. Build. Mater.* 25 [4], 2146–2156. https://doi.org/10.1016/j.conbuildmat.2010.11.015
5. Sá, G.; Sá, J.; de Brito, J.; Amaro, B. (2014) Inspection and diagnosis system for rendered walls. *Int. J. Civil Eng.* 12 [2], 279–290.
6. Silvestre, J.D.; de Brito, J. (2009) Ceramic tiling inspection system. *Constr. Build. Mater.* 23 [2], 653–668. https://doi.org/10.1016/j.conbuildmat.2008.02.007
7. Neto, N.; de Brito, J. (2011) Inspection and defect diagnosis system for natural stone cladding (NSC). *J. Mater. Civil Eng.* 23 [10], 1433–1443. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000314
8. Amaro, B.; Saraiva, D.; de Brito, J.; Flores-Colen, I. (2013) Inspection and diagnosis system of ETICS on walls. *Constr. Build. Mater.* 47, 1257–1267. https://doi.org/10.1016/j.conbuildmat.2013.06.024
9. Walter, A.; de Brito, J.; Grandão Lopes, J. (2005) Current flat roof bituminous membranes waterproofing systems - inspection, diagnosis and pathology classification. *Constr. Build. Mater.* 19 [3], 233–242. https://doi.org/10.1016/j.conbuildmat.2004.05.008
10. Garcez, N.; Lopes, N.; de Brito, J.; Silvestre, J.D. (2012) System of inspection, diagnosis and repair of external claddings of pitched roofs. *Constr. Build. Mater.* 35, 1034–1044. https://doi.org/10.1016/j.conbuildmat.2012.06.047
11. Garcia, J.; de Brito, J. (2008) Inspection and diagnosis of epoxy resin industrial floor coatings. *J. Mater. Civil Eng.* 20 [2], 128–136. https://doi.org/10.1061/(ASCE)0899-1561(2008)20:2(128)
12. Silva, C. da; Coelho, F.; de Brito, J.; Silvestre, J.; Pereira, C. (2017) Inspection, diagnosis and repair system for architectural concrete surfaces. *J. Perform. Constr. Fac.* 31 [5], 04017035. https://doi.org/10.1061/(ASCE)CF.1943-5509.0001034
13. Santos, A.; Vicente, M.; de Brito, J; Flores-Colen, I.; Castelo, A. (2016) Inspection, diagnosis, and rehabilitation system of door and window frames. *J. Perform. Constr. Fac.* 31 [3], 04016118. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000992
14. Gaião, C.; de Brito, J.; Silvestre, J.D. (2012) Gypsum plasterboard walls: inspection, pathological characterization and statistical survey using an expert system. *Mater. Construcc.* 62 [306], 285–297. https://doi.org/10.3989/mc.2011.62210
15. Van den Bulcke, J.; de Windt, I.; Defoirdt, N.; de Smet, J.; Van Acker, J. (2011) Moisture dynamics and fungal susceptibility of plywood. *Int. Biodeter. Biodegr.* 65 [5], 708–716. https://doi.org/10.1016/j.ibiod.2010.12.015
16. COAM (Colegio Oficial de Arquitectos de Madrid) (1991) Pathology, conservation and rehabilitation of buildings (in Spanish), Volumes 1, 3 and 4, Colegio Oficial de Arquitectos de Madrid, Spain.
17. Esteban, L.; Casasús, A.; Oramas, C.; de Palacios, P. (2002) Wood and its technology (in Spanish), Ediciones Mundi-Prensa, Fundación Conde del Valle de Salazar AiTiM, Madrid, Spain.
18. Hiziroglu, S. (2004) Dimensional changes in wood. NREM-5009, Oklahoma State University, Division of Agricultural Sciences and Natural Resources, USA.
19. Keskin, H.; Tekin, A. (2011) Abrasion resistances of cellulosic, synthetic, polyurethane, waterborne and acid hardening varnishes used woods. *Construc. Build. Mater.* 25 [2], 638–643. https://doi.org/10.1016/j.conbuildmat.2010.07.028
20. Kim, S., Kim, H.-J. (2006) Anti-bacterial performance of colloidal silver-treated laminate wood flooring. *Int. Biodeter. Biodegr.* 57 [3], 155–162. https://doi.org/10.1016/j.ibiod.2006.02.002
21. Makepeace J. (1993) The encyclopaedia of wood, Facts on file, New York, USA.
22. Merino, F. (1998) Pathology and intervention techniques, Volume 3 - Structural elements. Cap. III - Recovery of wood structures. Pathology of wood (in Spanish). Departamento de Construcción y Tecnología Arquitectónicas, Universidad Politécnica de Madrid, Editorial Munilla-Lería, Madrid, Spain, 255–276.
23. Baar, J.; Debnáriková, V.; Rademacher, P. (2015) Influence of surface damage on moisture behavior and decay susceptibility of film faced plywood. *Pro Ligno* 11[4], 253–259.
24. Neto, N.; de Brito, J. (2012) Validation of an inspection and diagnosis system for anomalies in natural stone cladding (NSC). *Constr. Build. Mater.* 30, 224–236. https://doi.org/10.1016/j.conbuildmat.2011.12.032
25. Chong, W.-K.; Low, S.-P. (2005) Assessment of defects at construction and occupancy stages, *J. Perform. Constr. Fac.* 19 [4], 283–289. https://doi.org/10.1061/(ASCE)0887-3828(2005)19:4(283)
26. Ransom, W.H. (1987) Building failures: diagnosis and avoidance. Spon Press, Second edition, UK.
27. Minne, E.; Crittenden, J.C. (2015) Impact of maintenance on life cycle impact and cost assessment for residential flooring options. *Int. J. Life Cycle Ass.* 20, 36–45. https://doi.org/10.1007/s11367-014-0809-z
28. Ishak, S.N.H.; Chohan, A.H.; Ramly, A. (2007) Implications of design deficiency on building maintenance at post-occupational stage. *J. Build. Apprais.* 3 [2], 115–124. https://doi.org/10.1057/palgrave.jba.2950061
29. Nejad, M.; Shafaghi, R.; Ali, H.; Cooper, P. (2013) Coating performance on oil-heat treated wood for flooring. *Bioresources* 8 [2], 1881–1892. https://doi.org/10.15376/biores.8.2.1881-1892