

Article

Harmonised Classification of the Causes of Defects in a Global Inspection System: Proposed Methodology and Analysis of Fieldwork Data

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Abstract: This research results from the development of a global inspection system based on previous studies about individual expert inspection systems for 12 types of elements/materials of the envelopes of current buildings. The research focuses on the rational harmonisation of the causes of defects in a global classification list, established from 12 individual lists. The process considers predetermined criteria, including guidelines for merging, splitting and combining causes to reach a comprehensive and simple list. The frequency of the prescription of causes of defects is analysed and the causes “C-D12 Dampening of the cladding system” in painted façades and “C-B7 Use of unprescribed, inadequate, incompatible, low-quality, non-certified and/or non-approved materials” in natural stone claddings stand out. Additionally, when analysing the relationship of causes with defects, some causes are highlighted because they are considered direct causes of defects in a broad range of building elements/materials, namely: “C-C9 Accidental collisions with the cladding”, “C-C7 Intentional collisions/vandalism”, “C-D2 Excessive, insufficient or differentiated solar radiation”, “C-D8 Presence of rainwater or snow” and “C-D12 Dampening of the cladding system”. The proposed list of causes successfully gathers causal knowledge on the pathology of the non-structural building envelope in a single component, homogenising the vocabulary used for several building elements/materials.

Keywords: building inspection system; building envelope; building pathology; causes of defects; direct and indirect causes

1. Introduction

Technical building inspection procedures are enhanced with the adoption of standard activities. Inspection systems are a means to direct the surveying process with consistent procedures through its several stages [1], additionally normalising the set of vocabulary used to assess building pathology and prescribe further action. Consequently, the collection of data becomes systematised and the development of inspection reports becomes easier and more uniform, while the information provided is more comprehensive [2]. The objective of developing a building inspection system varies. It may be associated with the need to collect technical data on a specific set of building elements or materials [3–5], a predetermined building typology [6–8] or a neighbourhood/urban area [9,10].

While systemising the knowledge on building pathology, including diagnosis methods and repair techniques, the authors’ research team, from Instituto Superior Técnico (IST), University of Lisbon (UL), developed a set of expert inspection systems. The making of the individual building inspection systems at IST-UL is described by Ferraz et al. [11]:

- Each one applies to a non-structural building element or a cladding material;
- They are based on the literature and inspection experience;

- Four entities are defined and classified, namely defects, probable causes, diagnosis methods and repair techniques;
- Semi-quantitative correlations are attributed between these entities and defects in matrices;
- Fieldwork data are collected from representative samples;
- Fieldwork data are used to validate the inspection systems.

With several inspection systems developed under these same principles, a vast understanding of building pathology was put together. However, as building inspection does not usually focus on a single type of building element/material, surveyors would have to use different systems to assess different building elements/materials in a single building. To avoid this, a global building inspection system for the building envelope (roofs, façades and floorings) is under development at IST-UL, based on those previously devised individual expert knowledge-based inspection systems for distinct types of building elements/materials.

The dispersion of information through different inspection systems, or in the literature, may discourage the use of an organised method during building inspections, thus making the results more dependent on the surveyor's knowledge and experience, and hence are more likely to be biased. Less reliable inspection results affect the effectiveness of repairs.

The development of the global building inspection system is directed at building surveyors, who may use it to complement and improve their processes. The use of this system may be helpful in cases of insurance claims, maintenance planning and building assessment and valuation. Furthermore, the global building inspection system may also support architects and engineers when mandatory building inspections are not required nor performed by other professionals, but are necessary for refurbishment purposes. Such a tool may prove its usefulness in all those cases, considering its validity and comprehensiveness.

The global building inspection system under development at IST-UL is novel when compared with known ones (from the literature or commercial solutions) because it combines different types of elements of the building envelope in one methodology. Moreover, it may be used in several contexts, such as urban or rural areas, and in varied building typologies. The global inspection system has a strict structure based on classification lists and correlation matrices, complemented by: detailed files with further information and an atlas of defects composed of short descriptions and photographs, with varying levels of repair urgency according to the type of defect, building element/material and degradation conditions.

Even though the inspection of buildings listed as historical should be systematised, it should also be the result of a customised approach. For this reason, historical buildings are excluded from the scope of the global building inspection system. Instead, it focuses on current buildings, including housing, office, commercial, education, cultural and administrative buildings.

Following the structure of the individual expert inspection systems, the global building inspection system includes classification lists of defects, their causes, diagnosis methods and repair techniques, correlation matrices between the defects and the other entities and an inter-defects correlation matrix [11]. This system offers additional information about the listed defects, diagnosis methods and repair techniques in detailed files that will help surveyors in identifying defects, performing a diagnosis and prescribing the best course of action [12]. The global system also includes a broad inspection form.

The development of the aforementioned global inspection system requires a harmonisation methodology to homogenise the system's components so that they become applicable to different building elements/materials within its scope. The harmonisation of classification lists is a way of standardising the used language and promoting user-friendly lists [13]. Harmonised classifications allow using the same designation to identify a defect or a cause consistently, independently of the cladding material or building element. Moreover, different parties in the construction sector may communicate better by using a uniform language.

The global system's harmonised classification lists of defects, diagnosis methods and repair techniques have already been presented [14–16], but the harmonised classification of causes of defects is still missing from the literature.

The investigation of building pathology includes the identification of defects, their causes and the origin of those causes. This paper focuses on the causes of defects, but, in this field, it is important to clarify each concept. A defect is an observable manifestation of the failure of a building part, element, component or material, according to its expected performance [17]. A cause of a defect is an event, static or dynamic through time, that instigates the failure of building parts, elements, components and materials [18]. The cause of a defect is not usually unique but is, instead, a set of causes that forms a chain of events that lead to the appearance of an observable phenomenon that is called a defect. The origin of the causes, also known as the root cause, consists of pinpointing the agent responsible for setting the degradation mechanism in motion (e.g., inclement weather originated in the surrounding environment).

An incomplete repair of a defect is likely to lead to its reoccurrence, as the conditions for it to progress stay unchanged. On the other hand, the elimination of the causes of a defect prevents its reoccurrence but does not necessarily repair the defect itself. In other words, even if the conditions of the development of the defect are no longer present, it is still necessary to do something about the existing manifestation of failure. So, the combination of the repair of defects with the elimination of their causes is the adequate process to completely restore the performance of building elements.

A maintenance approach based on a reactive strategy of carrying out corrective repair works leads to consecutively executing the same type of intervention, as defects will keep reappearing. Such a strategy results in higher levels of construction and demolition waste and resource consumption. Alternatively, maintenance approaches may be proactive (preventive and predictive) [19], including preventive repair and maintenance works, the former including the elimination of the causes of defects and the repair of defects. This type of works is expected to decrease the number of interventions in existing buildings, thus resulting in lower amounts of construction and demolition waste and resource consumption. Correctly diagnosing the causes of defects is paramount to performing preventive repair works.

Additionally, deep knowledge about the probable causes of defects allows for setting a group of actions in motion concerning the erection of new buildings and the refurbishment of existing ones [20,21]. If they are aware of the causes of defects, designers and contractors can avoid the same mistakes and are capable of providing more efficient responses to aggressive agents. This is a threefold accomplishment, acting on the (i) construction stage (design and execution) and on the (ii) operation and maintenance stage of the building's life cycle, while (iii) trying to delay the last stage (end of life) [22].

The main research question this paper tries to answer is: how can a classification list of causes applicable to the whole building be achieved? So, this research intends to propose such a list of causes and the methodology to elaborate it. The element/material-specific lists of causes are used and iteratively integrated. Moreover, the research measures the most frequent causes of defects, considering the scope of affected building elements/materials, and analyses the direct and wide-ranging nature of some causes.

This paper presents a short literature review of classifications of the causes of defects and contextualises the development of a global building inspection system. Then, the materials and methods are summarised. The results include the harmonisation criteria and the proposed list of the causes of defects, as well as analyses of the frequency data of causes (based on fieldwork data) and of the defects–probable causes correlation matrix.

1.1. Causes of Defects in the Building Envelope—Literature Review

Urbanowicz's [23] review of the most common building defects presents a general and concise classification of causes. Three categories are considered, with the following percentages: 50% of defects are recorded to be caused by poor design, 35% by poor construction and 15% by external

factors. According to this research, poor design includes: choice of material or component unsuitable for the intended purpose; details ineffective in controlling water penetration; and lack of adequate provision for movement (creation of joints). Poor construction refers to poor workmanship and lack of care, the contravention of requirements and the incorrect use of materials. As for external factors, they comprise weather factors, like sun, rain and wind, or biological factors, pertaining to insect attack and fungi.

Porteous's [17,18,24] research on building failures identifies different ways of attributing causality. The primary causes of defects are inadequate briefing, inadequate design, errors in construction or defects in materials and components. This classification excludes external aggressive agents. On the other hand, "basic" causes of defects are also identified, namely dampness, movements and chemical/biological change.

Josephson and Hammarlund [25], in their study about defects in construction, present a classification of causes of defects focused on the human perspective (designers and contractors), and thus on human error. Five categories of causes are determined: knowledge, information, motivation, stress and risk. Considering the total defects' cost, 50% is attributed to motivation, which mainly affects site management, workmanship and subcontractors. The cost of defects attributed to design teams is mainly caused by (a lack of) knowledge.

Olubodun [26] explores relationships between the primary causes of defects in public housing stock through factor analysis. The extracted factors were considered to be causative phenomena of identifiable defects, namely: dwelling external influence; design integrity standard of dwelling; tenant's lack of care index; the influence of a changing and evolving standard; ageing influence; vandalism; design and construction inadequacy; accidental damage; dwelling orientation; and soil condition. The last factor accounts for 4% of the sample's variance, while the first factor includes 16% of the total variance, both referring to the external conditions of the dwelling.

Chong and Low [27] assessed defects at the construction and occupancy stages, also identifying their causes. The frequency of design, workmanship, material, lack of protection and maintenance causes was analysed according to the building element and stage of occurrence (construction or occupancy). Mechanical and electrical elements presented 73% of defects associated with design issues at the occupancy stage. On the other hand, for internal walls, 89% of defects were caused by workmanship issues occurring at the construction stage.

Watt's [28] research on building pathology includes a classification of the causes of defects to assess agents and mechanisms that affect buildings. Natural and anthropogenic risk factors are listed, including the categorisation of nature, timing (long-term, rapid onset and medium-term), scale (local, regional or global), and probability (continuous, continuous cycles, infrequent, rare or frequent) of each factor. Natural factors are subdivided into (i) biological and (ii) meteorological factors, and (iii) geochemical and (iv) natural hazards. Anthropogenic risk factors are subdivided into (i) pollution, (ii) mass tourism, (iii) management, (iv) inappropriate use, (v) bad care, (vi) remedial works and (vii) human hazards. The nature of the factors may be biological, physical, physicochemical, chemical, architectural and environmental.

Some research on the minimisation of defects in building construction projects also refers to their causes [29]. Defects in building construction projects are attributed to poor design, low-quality workmanship, construction not according to design or the exposure of the building to factors not allowed for in the design. Additionally, the research mentions the influence of the buildability of the design on the performance of workmanship and of the durability of building materials.

Bortolini and Forcada [30] propose a model for assessing a building's condition, based on a Bayesian network approach. In this study, five basic conditions were identified as having a causal influence on the occurrence of defects: design and construction errors; environmental conditions; façade type; façade preventive maintenance; and façade age. Different probabilities of the occurrence of states within those conditions were quantified. For instance, there was a 70% probability of a

façade not being subjected to preventive maintenance, thus influencing the occurrence of detachment, water problems and cracking.

The RehabiMed Method [31], referring to the rehabilitation of buildings with traditional Mediterranean architecture, presents the main causes of degradation of stone: rising damp and dampness from the rain; chemical causes, biological factors and atmospheric pollution; and mechanical causes (loading and stresses). According to the same method, mudbricks are mainly degraded due to water and dampness, biological factors and mechanical stresses. Timber damage is associated with temperature and humidity variations, biological causes and structural problems.

Kim et al. [21] identified a limited set of causes of defects in residential buildings: neglect of supervision; pressing schedules; construction by inexperienced workers; defects in materials; and inadequate inspection. In summary, this study claimed that defects are mainly caused by human or process errors, excluding external agents from the cause–effect binomial.

Another study, on architectural defects in a university building in Malaysia [32], also focused on their causes. The most frequently detected causes were: work not according to specification; poor workmanship; lack of protection; vandalism; and water seepage.

Wilson and Harrison [33], referring to the assessment of claddings, list the basic reasons for their failure. Weathering problems (durability), temperature effects (movement) and damage (impact, explosion) are considered external factors, while lack of or poor fixing, structural movements of the building and material breakdown are considered internal factors of failure. The same authors refine their investigation on the causes of failure of claddings by considering four types of failure: structural building failure; cladding failure; failure of fixing methods/fixing components; and workmanship. Examples of the causes of such failures are given in detailed lists, including the chemical attack and corrosion of structural elements, poor soil conditions, vibration, lack of movement joints, stone not appropriate for the application, incorrect choice of fixing metal, poor installation and poor site supervision, among many others.

A study about external mortar renders registered the most probable causes of defects according to the areas of the façade [34]. In walls without openings, differential movements and mortar shrinkage were identified as the causes of cracking, while the render's texture was associated with the accumulation of dust and pollution particles. In parapet walls and below eaves, wind-driven rain, free water flow and the lack of adequate coping and projecting roof eaves were appointed as the main causes of defects. At ground level, the direct incidence of rainwater, splashes of rainwater and rising damp were the most common reasons for the appearance of defects. Around openings, defects were mainly caused by stress concentration in their corners, but the poor detailing of windowsills, without drips or with drips incorrectly designed, also played an important role. In protruding corners and the edges of façades, differential movements were the main cause of cracking. Below balconies and soffits, differential movements and mortar shrinkage were identified again as causes of cracking, and the absence of or poorly designed drips also caused degradation in these areas. The study lacked a systematised presentation of results concerning causes, as only defects were analysed in the presented statistical results.

Kvande et al. [35] reviewed the durability of external thermal insulation composite systems (ETICS) on walls in Norway using the SINTEF Building Defect Archive. This research identified 15 different causes of defects, presenting a ranking of the most frequent ones, where “defects associated with flashings against precipitation” stands in first place (maybe because of the location), with a relevant contribution of buildings investigated between 2003 and 2017. Buildings investigated between 2003 and 2007 also presented a significant number of cases whose defects were associated with “insufficient thickness of render”. Moreover, in buildings investigated between 1998 and 2002, defects tended to be associated with “incorrect reinforcement mesh” and, in buildings investigated between 1993 and 1997, with “faulty render mix or undesirable setting conditions”.

1.2. Context of Development of a Global Inspection System

The global inspection system under development at IST-UL is based on a set of 12 individual expert inspection systems developed by different members of the research team, each one focusing on a single type of element/material of the building envelope (Table 1): external claddings of pitched roofs; flat roofs; door and window frames; wall renders; ETICS; painted façades; architectural concrete surfaces; adhesive ceramic tiling; natural stone claddings; wood floorings; epoxy resin industrial floor coatings; and vinyl and linoleum floorings. The identical structure of all individual expert inspection systems is transposed to the global system, comprising: the classification of defects and the causes of defects, diagnosis methods and repair techniques; correlation matrices between these entities; detailed files of defects, diagnosis methods and repair techniques; and inspection forms [11]. All individual systems were validated in inspection campaigns comprising significant building samples (Table 1).

The classification lists of the causes of defects in each expert inspection system include all foreseeable causes that may influence the deterioration of the corresponding building element. They are expected to be useful for surveyors while diagnosing pathological phenomena detected in building envelopes, as part of different types of building inspections. Still, regular inspections, determined by maintenance plans, are preferred as part of predictive maintenance strategies, which are based on the real conditions of building elements [36]. Nevertheless, knowledge regarding the causes of defects is also a determinant for preventive maintenance.

The individual classification lists of the causes of defects were organised in categories according to a theoretical timeline of degradation (Table 1). These lists were validated through the analysis of the frequency of the identification of causes, considering the relevance of the causes of defects not identified during fieldwork [37].

The objective of providing surveyors with a single list of the causes of defects required the collection of the individual lists within all expert inspection systems, gathering a comprehensive set of relevant causes considering the limited scope of building elements/materials. The overlap of the causes of defects in different lists justified a merging process. That is the case for “missing/incorrect design/detailing of the ventilation systems” (Figure 1), which was defined in the lists of external claddings of pitched roofs and door and window frames [38,44], resulting in biological growth on the surface of roof tiles and surface moisture (condensation) on window frames and glazing.

After the merging process, the classification list was still too long, failing to correspond to a reduction objective. So, a grouping process was started, consisting of combining similar causes of defects within broader ones by associating those with a similar scope. For instance, 10 out of 12 classification lists included at least one of the following [37,38,44,46,48,49,51,56,58,60]: use of non-prescribed, inadequate or incompatible materials; use of poor quality and/or uncertified materials; application of weak or cracked stone slabs; use of excessively dry or wet wood; setting of warped or defective wood elements; finishing layer unsuited to use; use of materials that are inadequate, of low quality and/or non-certified; presence of water-soluble salts in moisture or in the materials employed; lack of sufficient water vapour permeability in rendering or painting; use of dark colours on exterior walls; insufficient dimensional stability of the insulation material; inadequate protection against microorganisms of the finishing biocide; metal elements with no protection against corrosion; finishing coat of insufficient water permeability; plates of non-uniform thickness; and disregard of specifications/unconformity between design and execution. These causes were condensed into a single entity named “use of unprescribed, inadequate, incompatible, low-quality, non-certified and/or non-approved materials”, an execution error encompassing a wide range of specific actions or non-compliance issues. In this way, a shorter classification list of the causes of defects was built.

Table 1. Expert inspection systems developed at Instituto Superior Técnico (IST), University of Lisbon (UL), that were the basis of the global inspection system.

References	Building Elements/Materials	Groups of Causes of Defects in the Classification List	Validation Sample	Average Number of Causes per Detected Defect	
[38,39]	Roofs	external claddings of pitched roofs (ECPR)	C-P Design errors; C-E Execution errors; C-M Mechanical actions; C-A Environmental actions; C-U Use/maintenance errors	207 surfaces; 164 buildings	2.38
[40–42]		flat roofs (FL)	C-P Project/design errors; C-E Execution errors; C-A Environmental actions; C-U Maintenance/use errors; C-M External mechanical actions	105 surfaces; 105 buildings	3.35
[43,44]	Façade elements	door and window frames (DWF)	C-P Project/design errors; C-E Execution and assembly errors; C-M Mechanical actions; C-A Environmental and biological actions; C-U Use and maintenance errors	295 frames; 96 buildings	2.01
[45,46]		wall renders (WR)	C-C Design errors; C-E Execution errors; C-M Environmental actions; C-A Mechanical actions; C-U Wear and maintenance faults	150 surfaces; 55 buildings	2.68
[47,48]	Façade claddings	external thermal insulation composite systems (ETICS)	C-M Material selection; C-C Design; C-E Application; C-A Environmental actions; C-H External mechanical actions; C-U Maintenance	146 façades; 14 buildings	2.31
[49,50]		painted façades (PF)	C-F Manufacturing/storage defects; C-C Design errors; C-E Execution errors; C-A Environmental agents; C-U Usage/maintenance errors	105 façades; 41 buildings	7.37
[51,52]		architectural concrete surfaces (ACS)	C-P Design errors; C-E Execution errors; C-A Environmental actions; C-M Mechanical actions; C-G Aggressive agents; C-U Use and maintenance	110 surfaces; 53 buildings	3.00
[37,53,54]	Façade claddings and floorings	adhesive ceramic tiling (ACT)	C-A Design errors; C-B Execution errors; C-C Accidental actions; C-D Environmental actions; C-E Lack of maintenance; C-F Changes from initially predicted conditions	88 surfaces; 46 buildings	4.51
[55,56]		natural stone claddings (NSC)	C-P Design errors; C-E Execution errors; C-M Exterior mechanical actions; C-A Environmental actions; C-F Faulty maintenance; C-I Changes in the conditions initially predicted	128 surfaces; 59 buildings	4.59
[57,58]		wood floorings (WF)	C-A Production errors; C-B Design errors; C-C Execution errors; C-D Exterior mechanical actions; C-E Biological actions; C-F Environmental actions; C-G Maintenance errors	98 floorings; 35 buildings	5.52
[59]	Floorings	epoxy resin industrial floor coatings (ERIFC)	C-A Design errors; C-B Execution errors; C-C Exterior mechanical accidental actions; C-D Environmental actions; C-E Utilisation errors	29 floorings; 23 buildings	4.48
[60,61]		vinyl and linoleum floorings (VLF)	C-A Design errors; C-B Execution errors; C-C External mechanical actions; C-D Environmental actions; C-E Maintenance errors	101 floorings; six buildings	1.56

Apart from that, building element/material-specific causes were kept separate in the list, especially when they result in severe defects. With this stipulation, the classification list of causes improved in its comprehensiveness. The deficient detailing of the reinforcement is an example of a cause particular to architectural concrete surfaces [51].

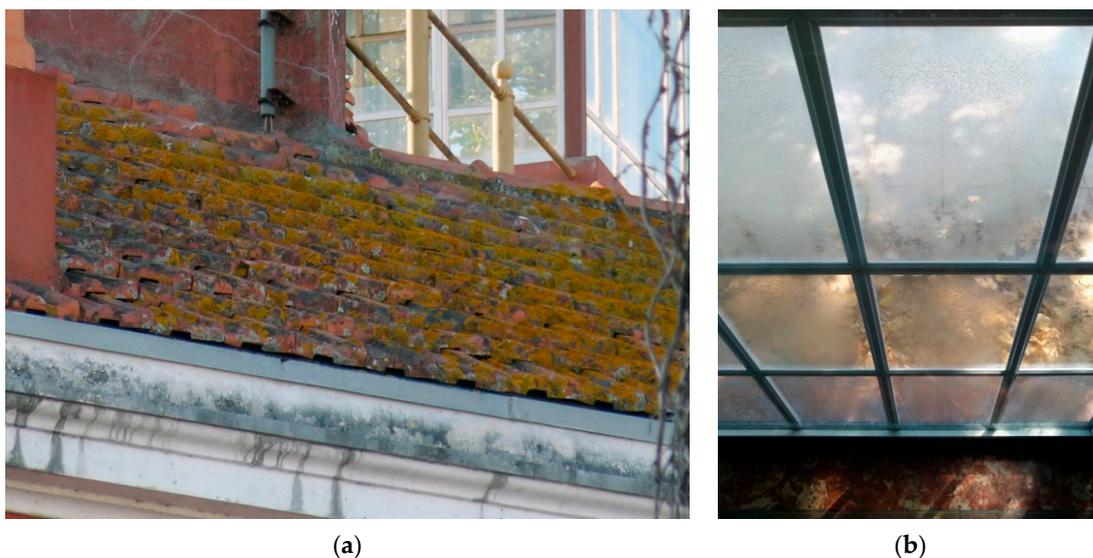


Figure 1. Examples of phenomena associated with faulty ventilation systems (C-A3): (a) biological growth on clay roof tiles of a pitched roof with signs of excessive use of mortar in the top ridge; (b) condensation inside a windowpane in a room with high levels of water vapour production and insufficient ventilation.

2. Materials and Methods

A set of research developed at IST-UL about the inspection, diagnosis and repair of non-structural elements of the building envelope constitutes the basis for the study presented in this paper. All the mentioned studies are listed in Table 1.

Three groups of information are considered for each type of building element/material: (i) the classification list of the causes of defects, (ii) the defects–probable causes correlation matrix, and (iii) the absolute frequencies of the identification of the causes of defects from the inspection campaigns' samples.

Aiming at the definition of a global classification list of the causes of defects for the building envelope, all the individual lists of causes were verified in parallel, to find similarities and discrepancies, guided by harmonisation criteria (addressed in Section 3.1.1).

After the global classification list of the causes of defects was developed, the absolute frequencies of the occurrence of the causes of defects in fieldwork were used to build theoretical relative frequencies of the harmonised causes of defects, leading to a comparison of those frequencies for various building elements/materials. The most relevant causes for each building element/material were thus highlighted.

The defects–probable causes correlation matrices developed in the individual expert inspection systems, for different building elements/materials, allowed for analysing the correlations between defects and their causes with a focus on direct (near) causes of defects and subsequent patterns, considering the specificity of each building element/material.

3. Results

3.1. Global Classification List of the Causes of Defects

3.1.1. Harmonisation Criteria

To yield a classification of the causes of defects that affect the elements and materials of the envelope of current buildings, based on causes previously defined in building inspection systems for individual types of elements/materials, the following criteria were considered:

1. Devising a comprehensive list of the causes of defects, nevertheless avoiding repetition;
2. Using descriptive, direct and wide-ranging language;

3. Preferably opting for causes that apply to a large number of building elements/materials considered;
4. Keeping particular causes (with short range) according to the severity of their effects;
5. Allowing the repetition of a designation only when it is justified by the inclusion of causes in different categories, thus in different phases of the degradation mechanism;
6. Organising the causes according to five categories, following a theoretical timeline of degradation;
7. Considering any material's manufacturing problems as causes associated with execution errors related to quality control;
8. Matching mechanical actions, environmental actions and use and maintenance errors with causes resulting from the in-service conditions of the building;
9. Using a limited set of terms so that the cause is identified as belonging to a specific category.

The third and the fourth criteria are essential to keep the list from being incomplete or too extensive. In the individual classification lists of causes, many items, from list to list, referred generically to the same concept in different words. That allowed for merging those causes into a single one, using broader terms (criterion two). Additionally, some causes are very specific to a type of building material or element, with significant effects that should not be disregarded or lightened through the combination of such a cause with another. For that reason, the fourth criterion needed to be specified.

The fifth criterion refers to specific causes that may occur in different stages of the degradation process. For instance, while observing a roof cladding, a surveyor may find problems in the fastening points due to the occurrence of cracking next to fasteners. Still, the assignment of causality, although being associated with fastening, may be distinguished between "C-A19 Missing/incorrect prescription of the fastening system" and "C-B19 Deficient fastening", the latter referring to incorrect execution and the former to incorrect design.

Another example of the application of the fifth criterion is vandalism. The set of actions included in such a broad concept may correspond to mechanical actions (e.g., breaking the glass of a windowpane) or to other use actions (e.g., drawing a *graffiti* tag on a wall, as illustrated in Figure 2a). For this reason, two different causes of defects refer to vandalism: "C-C8 Intentional collisions/vandalism" and "C-E5 Vandalism". Such causes derive from the individual classification lists of causes, which refer to both concepts [38,41,44,46,51,54,56,58,59].

The sixth criterion is useful to organise the extensive list of causes. The chronologically ordered categories are design errors, execution errors, mechanical actions, environmental actions and use and maintenance errors. Additionally, these categories associate causality with different types of origins, either the design and execution stages or the maintenance and operation stage of the life cycle of the building, the latter divided into mechanical, environmental and use and maintenance actions. In Figure 2b, a very wide crack in a wall is observed. At first glance, this defect is associated with mechanical actions on the wall caused by the roots of a tree. With the categories defined, the surveyor may immediately refer to the category of mechanical actions to look for the adequate type of cause.

To summarise, the categorisation properties include, in the category of design errors, all causes that potentiate building defects that could have been avoided at the design stage, whether through design and detailing or through the choice and prescription of materials, including the definition of adequate application methods. Execution errors refer to problems resulting from the careless implementation of the design or from inadequate execution choices when the design lacks detailing, including the deficient quality control of materials and the use of inappropriate tools. Mechanical actions are related to mechanical activity on the building element or the substrate of claddings, causing defects. Impacts, movements and stresses are included in this category. The category of environmental actions encompasses all the effects that affect the building element and are related to its surrounding environment, such as those generated by water, temperature and dirt. Finally, use and maintenance errors comprehend a set of actions over the building element that are specifically related to human action, whether through the current use of the cladding or via inadequate maintenance, cleaning or repair.



Figure 2. Examples of defects in the building envelope: (a) *graffiti* associated with vandalism and use and maintenance errors; (b) cracked wall due to mechanical actions.

Some individual expert inspection systems included “production errors” in their classification of the causes of defects (Table 1) [49,58]. As such a category was not adopted in the global classification list, a criterion was defined determining where to include those types of causes (criterion seven). In these cases, it was assumed that, if a material with manufacturing issues was used in the building, it was due to the poor quality control of materials on-site, and is thus an execution error.

Furthermore, some individual expert inspection systems mixed up the chronological order of the five basic categories within the life cycle of the building [48,58]. For instance, causes associated with unfavourable weather conditions during on-site works were associated with environmental actions, when, in fact, they should have been associated with execution errors. Although unfavourable weather conditions are clearly related to environmental conditions, the decision to perform construction works during those unfavourable conditions is a management decision. Moreover, categories of mechanical and environmental actions and of use and maintenance errors should correspond to causes occurring in the service life of the building, which is not the case for the aforementioned cause. Hence, the eighth criterion was stated.

The ninth criterion corresponds to choices in terms of language to implicitly associate some causes of defects with the determined categories. For instance, terms like “deficient design” and “incorrect design” are repeatedly used in the design error category, while “deficient application” and “incorrect execution” are terms tacitly associated with the category of execution errors. With the application of this criterion, the list is expected to be easier to read and understand.

3.1.2. Proposed Classification List of the Causes of Defects

Given the objectives of a global classification list of causes of defects, several iterations were performed until reaching a steady result, applying the described methodology and homogenisation criteria. In the first iteration, the list was composed of 300 causes of defects and, in the last, of 111. This number represents a list three times longer than that of defects [14], which is considered to be a balanced result, considering (i) the number of building elements/materials included in the

global inspection system and (ii) the causes–defects ratio in the classification list in each expert inspection system.

Table 2 shows the proposed classification list of the causes of defects, organised in five categories, as mentioned.

Table 2. Proposed classification list of the causes of defects within the global inspection system.

Code	Category	Code	Cause
C-A	design errors	C-A1	deficient design of the structure/support
		C-A2	deficient design/detailing of the slope
		C-A3	missing/incorrect design/detailing of the ventilation systems
		C-A4	missing/incorrect design/detailing of the thermal insulation system
		C-A5	missing/incorrect design/detailing of constitutive layers
		C-A6	deficient specification of layers' thickness
		C-A7	missing/incorrect design/detailing of pathway accessories for maintenance access
		C-A8	specification of inadequate or incompatible materials, or missing specification
		C-A9	insufficient functional classification of the elements for the aggressiveness of the environment
		C-A10	deficient application of regulations and/or specifications
		C-A11	deficient design/detailing of tail-end areas
		C-A12	deficient design/detailing of protruding elements
		C-A13	missing/incorrect design/detailing of singularities
		C-A14	missing/incorrect design/detailing of mechanical reinforcement systems
		C-A15	deficient design/detailing of expansion joints
		C-A16	missing/incorrect design/detailing of the water drainage system
		C-A17	deficient design/detailing of overlaps
		C-A18	poorly designed or insufficient cladding joints
		C-A19	missing/incorrect prescription of the fastening system
		C-A20	deficient design/detailing of the area next to the ground
		C-A21	detailing inadequate to the substrate
C-B	execution errors	C-A22	deficient specification of the clearances between the span and the frame and between the frame and the leaf in window and door frames
		C-A23	insufficient or badly distributed locks in window and door frames
		C-A24	lack of planimetry, when required, in epoxy resin floor coatings
		C-A25	missing/incorrect prescription of the application method/construction process
		C-A26	missing/incorrect prescription of the environmental conditions for application or substrate conditions and preparation in painted surfaces
		C-A27	inadequate prescription of formwork or form release agent in architectural concrete surfaces
		C-A28	deficient detailing of the reinforcement in architectural concrete surfaces
		C-B1	deficient compliance with the design project or tender specifications
		C-B2	use of inexperienced or poorly qualified/unspecialised labour
		C-B3	deficient application of the ventilation and thermal insulation elements
		C-B4	deficient application of layers
		C-B5	lack of precision in the execution of the lath or alignment of the external cladding elements in pitched roofs
		C-B6	incorrect handling of materials or use of inadequate tools
		C-B7	use of unprescribed, inadequate, incompatible, low-quality, non-certified and/or non-approved materials
C-B8	use of deficient materials due to the manufacturing process		
C-B9	deficient storage/transportation of materials		
C-B10	incorrect application of sealants		
C-B11	application in unfavourable/extreme weather conditions		
C-B12	missing/incorrect execution of tail-ends and associated protection elements		
C-B13	deficient execution of expansion joints		
C-B14	missing/incorrect execution/dimensioning of cladding joints		

Table 2. Cont.

Code	Category	Code	Cause
		C-B15	cladding laid continuously over substrate joints or over different substrate materials
		C-B16	deficiencies in the filling of joints
		C-B17	disregard for the cladding's stereotomy
		C-B18	deficient execution of the water drainage system
		C-B19	deficient fastening
		C-B20	missing/incorrect execution of slope
		C-B21	disregard for the pauses between execution stages
		C-B22	application in dirty, chalky, irregular or damp and unprepared substrates
		C-B23	inadequate thickness of the bedding material
		C-B24	use of bedding material with high shrinkage or expansion
		C-B25	deficient application of the span frame, the glass or the window and door frames in general, or deficient levelling of the leaves
		C-B26	deficient finishing coat
		C-B27	disregard for the composition or recommendations of the manufacturer or of the prescription, or for the formulation of the product in general
		C-B28	insufficient supervision/quality control
		C-B29	inadequate thickness of the cladding itself
		C-B30	deficient execution of joints between strengthening profiles and between insulation boards in ETICS
		C-B31	deficient treatment of singularities in ETICS
		C-B32	deficient overlap of reinforcement mesh in splices or of the finishing coat in ETICS
		C-B33	deficient execution of the finishing coat in ETICS
		C-B34	incorrect application of construction elements in ETICS
		C-B35	deficient casting/compaction/curing in architectural concrete surfaces
		C-B36	badly executed casting joint in architectural concrete surfaces
		C-B37	imprecise reinforcement positioning in architectural concrete surfaces
		C-B38	absent/deficiently applied form release agent in architectural concrete surfaces
		C-C1	deformation of the bearing structure/substrate
		C-C2	movements of a structural nature of walls or foundations
		C-C3	substrate-cladding differential movements
		C-C4	movement of people or vehicles over the claddings
		C-C5	excessive loads on roofs and floorings
		C-C6	excessive vertical loads on wall claddings
		C-C7	impacts of heavy objects resulting from inclement weather
		C-C8	intentional collisions/vandalism
		C-C9	accidental collisions with the cladding
		C-C10	stress concentration within the substrate
		C-C11	fragmentation of the substrate in expansion, peripheral or stone plate joints
		C-C12	vibrations
		C-C13	abrasion
		C-D1	wind
		C-D2	excessive, insufficient or differentiated solar radiation
		C-D3	chemical action of organic compounds or dirt
		C-D4	action of vegetation growth, fungi or mould
		C-D5	atmospheric contamination/pollution
		C-D6	accumulation of dust, dirt or small solid particles
		C-D7	temperature
		C-D8	presence of rainwater or snow
		C-D9	wet-dry cycles
		C-D10	freeze-thaw cycles
		C-D11	action of water vapour or high relative humidity
		C-D12	dampening of the cladding system
		C-D13	natural ageing
		C-D14	thermal shock

Table 2. Cont.

Code	Category	Code	Cause
		C-D15	action of chemical agents from the soil, cryptoflorescence and leaching
		C-D16	corrosion of fastening metallic elements and reinforcement
		C-D17	infestation by woodworms or termites in wood floorings
		C-D18	rising damp
		C-D19	erosion
		C-D20	alkali-silica reactions, sulphates or chlorides in architectural concrete surfaces
		C-D21	acids in architectural concrete surfaces
C-E	use and maintenance errors	C-E1	nonexistent or inadequate maintenance
		C-E2	missing/inadequate cleaning of debris
		C-E3	replacement of elements by others of different geometry or tonality in external claddings of pitched roofs
		C-E4	change of the originally planned use conditions
		C-E5	vandalism
		C-E6	insufficient ventilation
		C-E7	overly premature use of the flooring
		C-E8	incorrect handling of the movable parts and locking mechanism in door and window frames
		C-E9	accidental actions inherent to the occupation, movement and normal use of users
		C-E10	equipment failure
		C-E11	perforation of the system/inadequate hole through a wall in ETICS

Each cause corresponds to a code composed of the letter C (for cause), a hyphen, a capital letter (from A to E, according to the categories), and a sequential number within each category (e.g., C-A1, C-A2, C-B1, C-B2, C-C1, C-C2, C-D1, C-D2, C-E1, C-E2 and so on).

Cause “C-B32 Deficient overlap of reinforcement mesh in splices or of the finishing coat in ETICS”, for instance, resulted from the combination of two individual causes from the individual classification list for ETICS (Figure 3), namely: “insufficient overlapping of the reinforcement splices” and “deficient overlapping of the finishing coat” [48]. Both causes, individually, were specific to a cladding system and referred to overlaps, whether on the base or finishing coats of ETICS. By weighing the severity of the effects of such causes, the similarity between them, the overall level of detail and the choice of a shorter global list, C-B32 was created from a combination of two causes of defects.

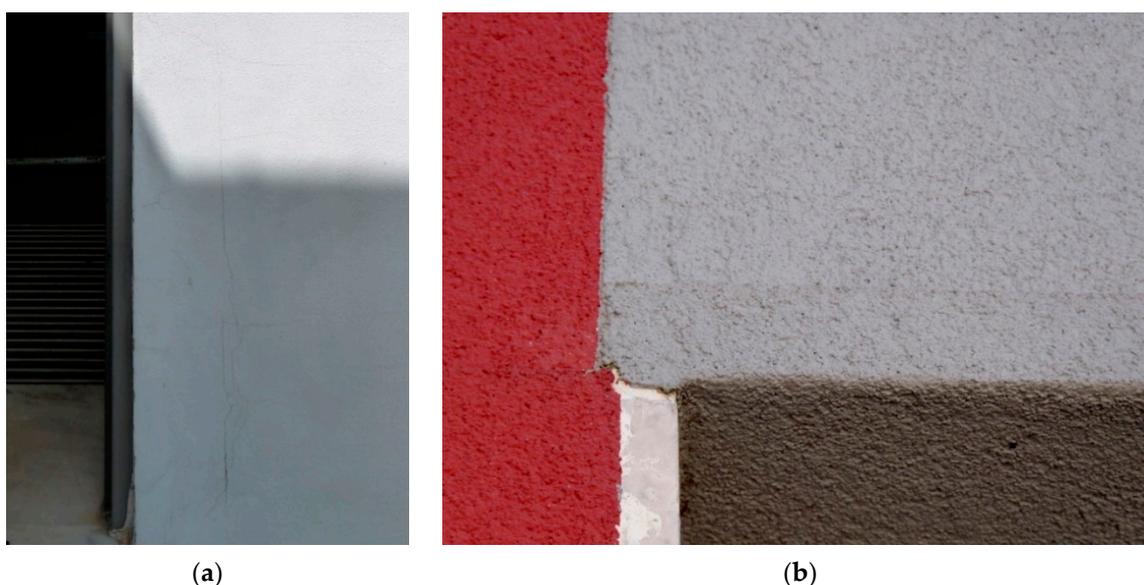


Figure 3. Examples of defect–cause relationships: (a) cracking in an ETICS surface due to insufficient overlapping of the reinforcement splices; (b) protrusion on an ETICS surface due to deficient overlapping of the finishing coat.

On the other hand, cause “C-D13 Natural ageing” was kept separate, as in the individual expert inspection systems [41,46,49,54,56,58–60]. Natural ageing was mentioned in eight individual lists of causes, always referring to a natural tendency that materials have to degrade over time (Figure 4a). So, the global list of the causes of defects inherently included natural ageing.

Cause “C-B36 Badly executed casting joint in architectural concrete surfaces” was also kept separate, even though it only applies to this type of cladding. In Figure 4b, the highlighted casting joint does not follow the stereotomy pattern of the whole surface, thus it must be considered non-compliant. This type of occurrence is very specific, not allowing for merging the cause with any other type of cause due to the execution specificities of architectural concrete surfaces. The effects of this cause are sufficiently severe to deserve special attention in the classification list of the causes of defects (fourth harmonisation criterion).



Figure 4. Examples of causes of defects: (a) degradation due to natural ageing in a window frame, a natural stone jamb and a wall render in a vacant house; (b) a deficient architectural concrete surface due to a badly executed casting/panel joint.

Choices resulting from the homogenisation process of the classification list of the causes of defects reflect on the use of the global inspection system, especially in the diagnosis procedure of a pathological phenomenon. Very specific causes of defects require a more profound knowledge of the technologies, execution process and behaviour of materials. General and more comprehensive causes only require a generic idea of the degradation mechanism that is in place. Surveyors using the IST-UL’s global inspection system, partially described here, are invited to use detailed files of defects to better characterise them (Figure 5). A section of those files refers to the probable causes of the occurrence of the defect, according to the defects–probable causes correlation matrix [62]. Browsing the suggested causes, the surveyor’s diagnosis is aided by the inspection system, nevertheless requiring familiarity with the causes under analysis. The more specific the cause, the more experienced and well-informed the surveyor must be.

File of defect										1/1		
A-B6 Corrosion in metallic fastening or tail-end elements												
Description												
In metallic materials, changes involving colour, runoffs, blistering, detachment, pitting and puncturing. In this case, these types of changes are only considered in fastening and tail-end elements.												
Field of application												
external claddings of pitched roofs (ECPR)				flat roofs (FR)				natural stone claddings (NSC)				
Probable causes												
0 - no correlation: no relation whatsoever (direct or indirect) between the defect and the cause; 1 - low correlation: indirect (first) cause of the defect, related only with the early stages of the deterioration process; (continues)												
ECPR FR NSC (continued) 2 - high correlation: direct (near) cause of the defect, associated with the final stages of the deterioration process. ECPR FR NSC												
C-A8	specification of inadequate or incompatible materials, or missing specification	1	2	1	C-B19	deficient fastening	0	0	1			
C-A11	deficient design/detailing of tail-end areas	1	1	0	C-B22	application in dirty, chalky, irregular or damp and unprepared substrates	0	0	1			
C-A16	missing/incorrect design/detailing of the water drainage system	0	0	1	C-D6	accumulation of dust dirt or small solid particles	0	0	1			
C-A19	missing/incorrect prescription of the fastening system	0	0	1	C-D8	presence of rainwater or snow	0	1	2			
C-B1	deficient compliance with the design project or tender specifications	1	0	0	C-D12	dampening of the cladding system	0	2	2			
C-B2	use of inexperienced or poorly qualified/unspecialised labour	1	0	0	C-D15	action of ground materials' chemical agents, cryptofluorescence and leaching	0	0	2			
C-B7	use of unprescribed, inadequate, incompatible, low quality, non-certified and/or non-approved materials	1	0	1	C-E1	inexistent or inadequate maintenance	0	1	1			
C-B7	use of unprescribed, inadequate, incompatible, low quality, non-certified and/or non-approved materials	1	0	1	C-E2	missing/inadequate cleaning of debris	0	0	1			
C-B7	use of unprescribed, inadequate, incompatible, low quality, non-certified and/or non-approved materials	1	0	1	C-E2	missing/inadequate cleaning of debris	0	0	1			
Possible consequences												
deformation, cracking or fracture in the cladding's current surface				rupture or detachment of fastening elements				affected aesthetical effect				
detachment of cladding elements				leakages/loss of watertightness				degradation of underlying materials and elements				
Aspects to inspect												
do deformation, cracking or fracture occur? (Y/N)				does subsequent detachment occur? (Y/N)				is the environment aggressive? (Y/N)				
compatibility of materials in contact with metallic elements				do water ponding or leakage occur? (Y/N)				extent of the defect		composition of the fastening set		
Diagnosis methods												
0 - no correlation: no relationship between the defect and the diagnosis method; 1 - low correlation: diagnosis method adequate to characterise the defect, although with some limitations; (continues)												
ECPR FR NSC (continued) 2 - high correlation: diagnosis method adequate to characterise the defect. ECPR FR NSC												
D-A1	endoscopy (ND)	0	0	1	D-C2	measurement of the in-depth humidity (D)	0	0	1			
D-A3	assessment of the slope, flatness, orthogonality and alignments (ND)	0	1	1	D-C3	infrared thermography (ND)	1	0	0			
Classification parameters												
may the defect progress? (Y/N)				users' safety				does subsequent detachment occur? (Y/N)		does subsequent loss of watertightness occur? (Y/N)		
Urgency of repair												
0 NSC: when the defect causes the detachment of cladding elements, threatening the users' safety.												
1 ECPR: when the defect causes the detachment of cladding elements; NSC: in the remaining situations.												
2 ECPR: when the defect causes the loss of watertightness of the cladding; FR: when conditions for the phenomenon to progress are present or when the defect causes the loss of watertightness of the cladding.												
3 ECPR: in the remaining situations; FR: in the remaining situations.												
4 -												
0 - imminent danger, contingency measures needed; 1 - need of immediate intervention; 2 - need of intervention in the short-term; 3 - need of intervention in the long-term; 4 - no urgent need, assess in the next inspection												
Repair techniques												
0 - no correlation: no relationship between the defect and the repair technique; 1 - low correlation: adequate repair technique within some adequacy constraints; (continues)												
ECPR FR NSC (continued) 2 - high correlation: the most adequate repair technique to repair the defect or eliminate its causes. ECPR FR NSC												
R-A11	replacement or reapplication of the cladding/glazing (partially or completely)	1	0	0	R-D5	repair/application of tail-ends and associated protection elements	1	2	0			
R-B11	change/replacement/repair of the fastening system or correction of the holes in the plates or substrate	1	0	0	R-D6	application/repair/replacement/cleaning of drainage systems/plumbing	0	2	0			
R-C2	repair/reinforcement/replacement of the bearing structure in pitched roofs	1	0	0	R-D7	removal of corroded or damaged metallic elements, with hole and notch filling (if applicable)	0	0	2			
-	-				R-D8	repair of water penetration spots	0	0	1			

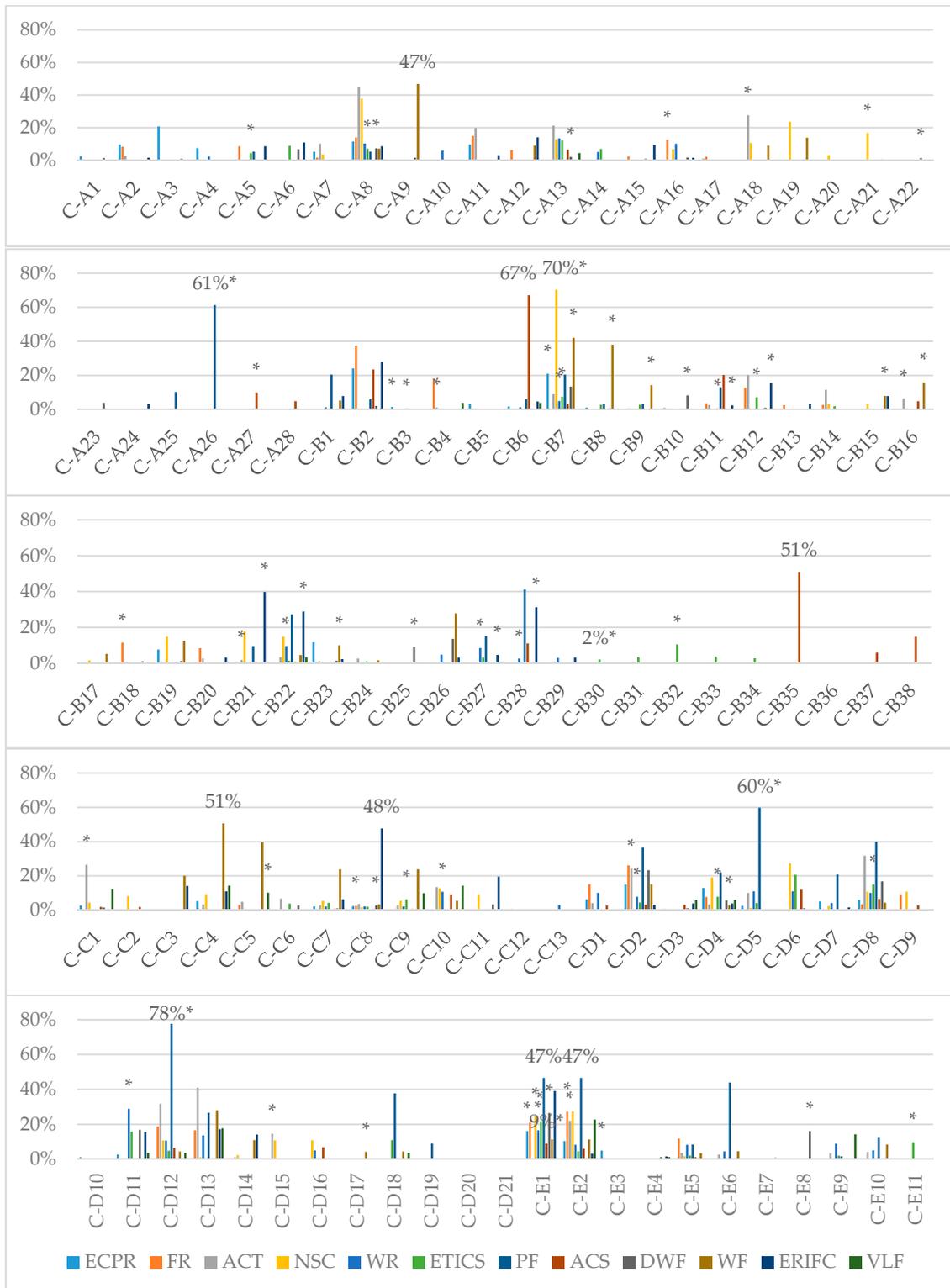
Figure 5. The file of defect “A-B6 Corrosion in metallic fastening or tail-end elements” with the section of probable causes highlighted.

3.2. Frequency of Causes of Defects

Using the data from the inspection campaigns performed to validate each expert inspection system (Table 1), the frequency of the identification of the causes of defects is subject to analysis in Figure 6. To develop the graph in this figure, first, the absolute frequencies of the identification of the causes of defects were adapted to the new global classification list. Then, those quantities were divided by the number of defects detected in each sample, thus obtaining the percentage of cases in which each cause was identified as a reason for the defect to occur.

The adaptation of the original data to the proposed classification of the causes of defects required some computation. In situations where individual causes were combined in a single global cause, the

absolute frequencies of the individual causes were added up. The results following those sums are marked with an asterisk in Figure 6.



* Resulting from a sum of absolute frequencies.

Figure 6. Relative frequency of the causes of defects identified in each expert inspection system.

Considering the top values in Figure 6, ten causes of defects stand out (starting with the most frequent one): “C-D12 Dampening of the cladding system” in painted façades; “C-B7 Use of

unprescribed, inadequate, incompatible, low-quality, non-certified and/or non-approved materials" in natural stone claddings; "C-B6 Incorrect handling of materials or use of inadequate tools" in architectural concrete surfaces; "C-A26 Missing/incorrect prescription of the environmental conditions for application or substrate conditions and preparation in painted surfaces"; "C-D5 Atmospheric contamination/pollution" in painted façades; "C-B35 Deficient casting/compaction/curing in architectural concrete surfaces"; "C-C4 Movement of people or vehicles over the claddings" in wood floorings; "C-C8 Intentional collisions/vandalism" in epoxy resin industrial floor coatings; "C-A9 Insufficient functional classification of the elements for the aggressiveness of the environment" in wood floorings; and "C-E1 Nonexistent or inadequate maintenance" and "C-E2 Missing/inadequate cleaning of debris" in painted façades.

These data should be analysed considering the average number of causes identified per detected defect during fieldwork, as presented in Table 1. This number is the highest in painted façades and the lowest in vinyl and linoleum floorings. So, it is not surprising that five of the most frequent causes are identified in painted façades. Moreover, vinyl and linoleum floorings are not one of the building elements/materials with very frequent causes.

Considering the data in Figure 6, the most cross-disciplinary causes, i.e., those that present the highest average numbers, can also be highlighted. That is the case for "C-E1 Nonexistent or inadequate maintenance", "C-B7 Use of unprescribed, inadequate, incompatible, low-quality, non-certified and/or non-approved materials", "C-E2 Missing/inadequate cleaning of debris", "C-D12 Dampening of the cladding system", and "C-D13 Natural ageing".

Moreover, on average, most defects are associated with environmental actions (C-D), as 0.91 causes in this category are identified per detected defect. Additionally, 1.68 causes per defect refer to causes resulting from in-service conditions (mechanical and environmental actions and use and maintenance errors), while 1.45 causes per defect refer to design and execution errors. These numbers do not match those mentioned by Urbanowicz [23], who recorded 85% of causes of defects to be associated with poor design and construction, while the data in Figure 6 associate 46% of causes with design and execution errors.

3.3. Relationship between Causes and Defects

Table 3 presents an analysis that was performed regarding the correlation matrix between defects and probable causes within the global inspection system. In the individual expert inspection systems, correlation matrices represent relationships between defects and probable causes, diagnosis methods and repair techniques. Those relationships are portrayed in tables whose cells are filled with 0s, 1s and 2s [59]. In the case of the defects–probable causes correlation matrix: 0 stands for no direct relationship between a defect and a cause; 1 stands for an indirect (first) cause of a defect related to the triggering of the deterioration process, which is an inessential cause for the development of the deterioration process, even though it may aggravate its effects; and 2 stands for a direct (near) cause of a defect, associated with the final stage of the deterioration process, one of the main reasons for the deterioration process and indispensable for its development [37].

A harmonised global correlation matrix between defects and probable causes transposes to a single matrix the correlation matrices of the individual inspection systems. Such a global matrix is composed of: rows corresponding to defects; columns corresponding to probable causes; and layers corresponding to building elements/materials, which is a third dimension added to the global matrix.

However, Table 3 only presents probable causes (in rows) and building elements/materials (in columns). Every probable cause that is highly correlated (correlation index 2) with at least one defect in a type of building element/material is thus marked with an X in the respective column. If the probable cause only has a low correlation or is not correlated (correlation indexes 1 and 0, respectively) with defects in all types of building elements/materials, the corresponding row in Table 3 is filled with hyphens.

Table 3. Causes that constitute probable direct causes of one or more defects within each layer of building elements in the global inspection system (marked with X).

Cause	ECPR	FR	ACT	NSC	WR	ETICS	PF	ACS	DWF	WF	ERIFC	VLF
C-A1	-	-	-	-	-	-	-	-	-	-	-	-
C-A2	X	X	X	-	-	-	-	-	-	-	-	-
C-A3	-	-	-	-	-	-	-	-	X	-	-	-
C-A4	-	-	-	-	-	-	-	-	-	-	-	-
C-A5	X	X	-	-	-	-	X	-	-	-	-	-
C-A6	-	-	-	-	-	-	-	-	-	-	-	-
C-A7	-	-	-	X	-	-	-	-	-	-	-	X
C-A8	X	X	X	-	-	-	X	-	-	-	-	-
C-A9	-	-	-	-	-	-	-	-	-	-	-	-
C-A10	-	-	-	-	-	-	-	X	-	-	-	-
C-A11	X	X	-	-	-	-	-	-	-	-	X	-
C-A12	-	-	-	-	-	-	-	-	-	X	X	-
C-A13	-	-	-	-	X	X	-	X	X	-	-	-
C-A14	-	-	-	-	X	X	-	-	-	-	-	-
C-A15	-	X	-	-	-	-	-	X	-	-	X	-
C-A16	-	X	-	-	X	-	-	-	X	-	-	-
C-A17	X	X	-	-	-	-	-	-	-	-	-	-
C-A18	-	-	X	-	-	-	-	-	-	X	-	-
C-A19	-	-	-	-	-	-	-	-	-	-	-	-
C-A20	-	-	X	-	-	-	-	-	-	-	-	-
C-A21	-	-	-	-	-	-	-	-	-	-	-	-
C-A22	-	-	-	-	-	-	-	-	-	-	-	-
C-A23	-	-	-	-	-	-	-	-	X	-	-	-
C-A24	-	-	-	-	-	-	-	-	-	-	-	-
C-A25	-	-	-	-	-	-	-	-	-	-	-	-
C-A26	-	-	-	-	-	-	X	-	-	-	-	-
C-A27	-	-	-	-	-	-	-	X	-	-	-	-
C-A28	-	-	-	-	-	-	-	-	-	-	-	-
C-B1	-	-	-	-	-	-	X	-	-	-	-	-
C-B2	X	X	-	-	-	-	X	X	-	-	X	-
C-B3	-	-	-	-	-	-	-	-	-	-	-	-
C-B4	-	X	X	-	-	-	-	-	-	-	-	-
C-B5	X	-	-	-	-	-	-	-	-	-	-	-
C-B6	-	-	-	-	-	-	X	X	-	-	-	-
C-B7	X	-	X	-	X	-	X	X	X	-	-	-
C-B8	X	-	-	-	-	X	X	-	-	-	-	-
C-B9	-	X	-	-	-	X	X	-	-	X	-	-
C-B10	X	-	-	-	-	-	-	-	X	-	-	-
C-B11	-	X	-	-	X	-	-	-	-	-	-	X
C-B12	X	X	-	-	-	X	-	-	X	-	X	-
C-B13	-	X	-	-	-	-	-	-	-	-	-	-
C-B14	-	X	X	X	-	X	-	-	-	-	-	-
C-B15	-	-	X	X	-	-	-	-	-	-	X	-
C-B16	-	-	X	-	-	-	-	X	-	X	-	-
C-B17	-	-	X	-	-	-	-	-	-	-	-	-
C-B18	-	X	-	-	-	-	-	-	X	-	-	-
C-B19	X	X	-	X	-	-	-	-	X	X	-	-
C-B20	-	X	X	-	-	-	-	-	-	-	X	-
C-B21	-	-	X	-	-	-	X	X	-	-	-	X
C-B22	-	-	X	X	X	X	X	-	-	-	-	X
C-B23	X	-	-	-	-	-	-	-	X	X	-	-
C-B24	-	-	X	-	-	X	-	-	-	-	-	-
C-B25	-	-	-	-	-	-	-	-	X	-	-	-
C-B26	-	-	-	-	-	-	-	-	X	X	X	-

Table 3. Cont.

Cause	ECPR	FR	ACT	NSC	WR	ETICS	PF	ACS	DWF	WF	ERIFC	VLF
C-B27	-	-	-	-	X	X	X	-	-	-	-	-
C-B28	-	-	-	-	X	-	X	X	-	-	-	-
C-B29	-	-	-	-	X	-	-	-	-	-	-	-
C-B30	-	-	-	-	-	X	-	-	-	-	-	-
C-B31	-	-	-	-	-	X	-	-	-	-	-	-
C-B32	-	-	-	-	-	-	-	-	-	-	-	-
C-B33	-	-	-	-	-	X	-	-	-	-	-	-
C-B34	-	-	-	-	-	X	-	-	-	-	-	-
C-B35	-	-	-	-	-	-	-	X	-	-	-	-
C-B36	-	-	-	-	-	-	-	X	-	-	-	-
C-B37	-	-	-	-	-	-	-	X	-	-	-	-
C-B38	-	-	-	-	-	-	-	X	-	-	-	-
C-C1	X	-	X	X	X	X	-	X	X	-	-	-
C-C2	-	-	-	X	X	X	-	X	-	-	-	-
C-C3	-	-	-	-	-	-	-	-	-	X	X	-
C-C4	X	X	X	X	-	-	-	-	-	X	X	X
C-C5	X	X	-	-	-	-	-	-	-	X	-	X
C-C6	-	-	X	-	-	-	-	-	-	-	-	-
C-C7	X	X	X	X	X	X	-	X	X	X	-	-
C-C8	X	X	X	-	X	-	-	-	-	X	X	-
C-C9	-	X	X	X	X	X	-	X	X	X	X	X
C-C10	-	-	-	X	X	-	-	X	-	-	-	-
C-C11	-	-	-	X	-	-	-	-	-	-	-	-
C-C12	-	X	-	-	-	-	-	-	X	-	X	-
C-C13	-	-	-	-	X	-	-	X	-	-	-	-
C-D1	X	X	-	-	X	-	-	-	-	-	-	-
C-D2	X	X	X	-	-	X	X	X	X	X	-	X
C-D3	X	-	-	-	-	-	-	X	-	-	X	X
C-D4	X	X	X	X	-	X	X	-	X	-	-	X
C-D5	X	-	X	X	X	-	X	-	-	-	-	-
C-D6	-	-	-	X	X	X	-	-	-	-	-	-
C-D7	X	-	-	X	X	-	X	-	X	-	-	-
C-D8	X	-	X	X	X	X	X	X	X	X	-	-
C-D9	-	X	-	-	-	-	-	X	-	-	-	-
C-D10	X	-	-	X	-	-	-	X	-	-	-	-
C-D11	X	-	-	-	X	X	-	-	X	-	X	X
C-D12	-	X	X	X	X	X	X	X	-	X	-	X
C-D13	-	X	X	X	X	-	-	-	-	X	-	X
C-D14	-	-	-	X	-	-	-	-	-	-	-	-
C-D15	-	-	X	X	-	-	-	-	-	-	-	-
C-D16	-	-	-	X	X	-	X	X	-	-	-	-
C-D17	-	-	-	-	-	-	-	-	-	X	-	-
C-D18	-	-	X	-	-	X	X	-	-	X	-	-
C-D19	-	-	-	-	-	-	-	-	-	-	-	-
C-D20	-	-	-	-	-	-	-	X	-	-	-	-
C-D21	-	-	-	-	-	-	-	X	-	-	-	-
C-E1	X	X	-	X	X	X	X	X	-	-	X	-
C-E2	X	X	-	X	-	-	X	-	X	-	X	X
C-E3	-	-	-	-	-	-	-	-	-	-	-	-
C-E4	-	X	-	-	-	-	-	-	-	-	X	-
C-E5	-	X	X	X	X	X	X	X	-	-	-	-
C-E6	-	-	-	-	-	-	X	-	-	-	-	-
C-E7	-	-	X	-	-	-	-	-	-	-	-	-
C-E8	-	-	-	-	-	-	-	-	-	-	-	-
C-E9	-	-	X	-	X	X	-	-	-	-	-	X
C-E10	-	-	X	-	X	-	X	-	-	-	-	-
C-E11	-	-	-	-	-	X	-	-	-	-	-	-

The analysis in Table 3 allows for determining the causes of defects that have a wider range of influence. Five causes of defects are highly correlated with defects in a significant number of types of building elements/materials, namely: “C-C7 Impacts of heavy objects resulting from inclement weather”; “C-C9 Accidental collisions with the cladding”; “C-D2 Excessive, insufficient or differentiated solar radiation”; “C-D8 Presence of rainwater or snow”; and “C-D12 Dampening of the cladding system”.

The group of the causes of defects with the most direct relationships with defects is “C-D Environmental actions” (12.9 defects per cause with correlation index 2 with probable causes in the category), but the group of the causes of defects with the most direct relationships with different types of defects is “C-E Use and maintenance errors” (1.9 unique defects (not considering repetition) per cause with correlation index 2 with probable causes in the category).

The defect that is most frequently directly related to probable causes is “A-C2 Oriented cracking on the current surface”. On the contrary, “A-D11 Clearances/gaps in door and window frames” is only directly correlated to “C-B25 Deficient application of the span frame, the glass or the window and door frames in general, or deficient levelling of the leaves” and “A-D11 Absent or damaged hinges or locks in door and window frames” to “C-A23 Insufficient or badly distributed locks in window and door frames”.

4. Discussion

The findings of this study should be seen in light of some limitations. The presented frequency of the results is limited by the samples of the cited studies, which may not reflect the general population, as they only refer to buildings in Portugal and, even in that scope, some building access issues may have conditioned the choice of case studies. Moreover, despite having benefited from the use of inspection systems, the collection of data from those samples was performed by different researchers and was prone to subjectivity and some imprecision, as inspections were merely visual. Although essentially based on the literature and experience, the defects–probable cause correlation matrices were validated using the same fieldwork data, which may have limited the definition of direct and indirect causes.

Nevertheless, the presented causes of defects are expected to be applicable to any geographical context, possibly with small adaptations to local construction characteristics or degradation phenomena.

Cause “C-D12 Dampening of the cladding system”, in painted façades, is the one most identified. The 78% relative frequency (Figure 6) is the result of the combination of two individual causes from the inspection system of painted façades (internal moisture and exterior water) [49]. That sample’s numbers were thus summed, but if the highest absolute frequency of those two causes were considered instead, the resulting figure would still be high (40%). Chong and Low [63] identified water seepage as the most recurring latent defect detected in external walls, constituting more than 1/3 of the sample of detected latent defects in external walls. These authors’ result is in line with the findings in Figure 6, although water seepage is different from the causes “dampening of the cladding system”. The research of Barrelas et al. [6], about the degradation of pavilions and prefabricated buildings in secondary schools, also highlights the presence of humidity as the main cause of defects in painting.

Figure 7 shows two different cases in which painted façades present the effects of such a cause. In Figure 7a, the colour of an outdoor ceiling (below a balcony) shows different tones in two stains that are approximately concentric. In the centre of those quarter circles (one larger than the other), whitish stains are found, giving the impression that efflorescence is occurring, in line with the common appearance of this phenomenon [64–66]. Two phenomena may be occurring, both dampening the surface: (i) the runoff of rainwater through the vertical surfaces of the balcony that then runs off through the lower horizontal surface of the balcony, as no drips to guide the water are observed or (ii) leakages in the waterproofing system of the balcony, reaching the lower surface of the slab. Whichever the case, staining and efflorescence are damaging the appearance of the surface, and more defects may start to occur soon, such as the peeling of the paint coating.

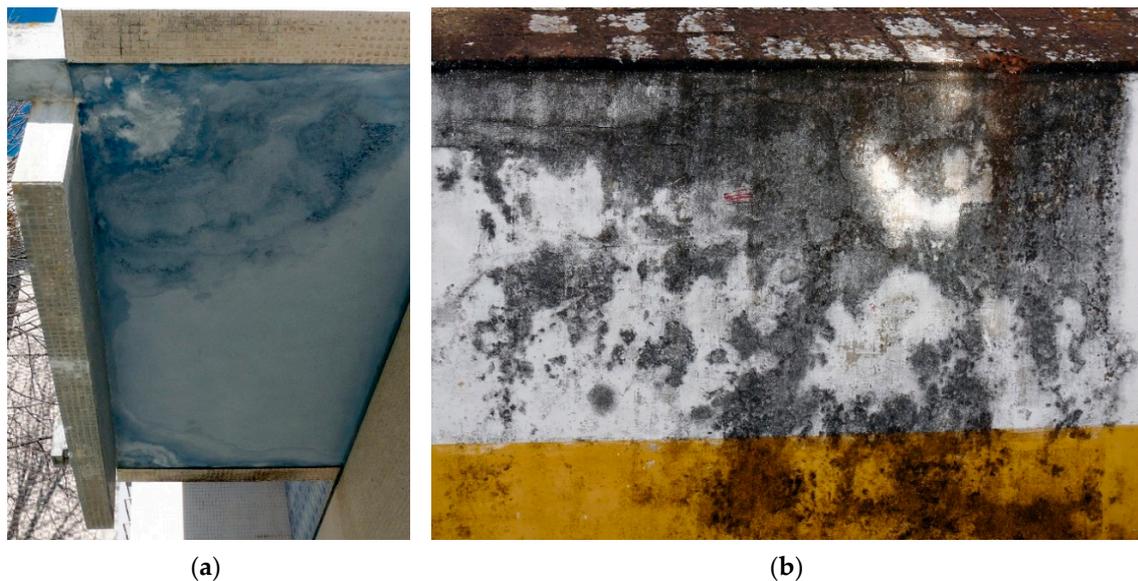


Figure 7. Result of dampening of the cladding system in painted façades: (a) colour changes and efflorescence; (b) dirt and biological growth.

In Figure 7b, blackish stains are observed, associated with the accumulation of dirt and biological growth. The upper sloped surface, above the vertical surface of the façade, promotes the runoff of rainwater through the façade. Dirt accumulated on the sloped surface is dragged by rainwater. Additionally, the lengthy drying period of the vertical surface stimulates the accumulation of dust and pollution particles from the atmosphere. Dirt and favourable moisture and lighting conditions result in the proliferation of mould on the surface.

Both situations illustrated in Figure 7 are commonplace in the degradation of painted façades. As these types of stains/colour changes mostly affect the aspect of the painted façade, Chai et al.'s [67] research only attributes a 0.25 weighting coefficient to such defects while determining the severity of the degradation of painted façades. Still, the aspect of painted façades can be compelling when deciding on the adequate moment to perform repainting works, as supported by Madureira et al.'s [68] results, which indicate that aesthetical defects constitute 87% of defects with an intervention priority of level 3 (short-term action, up to two years). According to Macarulla et al.'s [69] classification of defects, water problems constitute a defect, instead of a cause of defects, which can be further categorised as “excess moisture”, “entrapped water” and “water ingress”. These issues are only 1.92% of construction defects and 0.10% of post-handover defects. The considerable difference in these numbers from those presented in Figure 6 is probably associated with the moment of inspection; dampening/moisture issues are more likely to cause defects during the service life of buildings, and not immediately at the beginning of the in-service period. Lee et al. [70] show that, in residential buildings inspected 4–12 years after completion, 12.47% of detected defects refer to water problems.

“C-D12 Dampening of the cladding system” is also one of the causes with an average high frequency of occurrence, considering the twelve building elements/materials. Although painted façades stand out, adhesive ceramic tiling, flat roofs and natural stone claddings also show an incidence of this cause above 10%.

Moreover, C-D12 shows direct correlations with defects in nine out of 12 building elements/materials (Table 3). In seven out of those nine instances, “A-B1 Biodeterioration/biological growth” is appointed as an immediate result of dampness.

The identification of “C-B7 Use of unprescribed, inadequate, incompatible, low-quality, non-certified and/or non-approved materials” is very frequent in natural stone claddings (Table 3). In this type of building material, this cause results from the combination of three different causes from the individual expert inspection system, namely: “use of materials not prescribed in the design”;

“inappropriate use of materials”; and “application of weak or cracked stone slabs” [56]. So, the frequency reported in Figure 6 is the result of the sum of the three frequencies. If, instead of adding up the results associated with these individual causes of defects, the highest frequency of the three was to be considered, a relative frequency of 27% would be found. That logic would correspond to the assumption that the three individual causes were generally identified simultaneously, which is not the assumption inherent in Figure 6.

Figure 8a shows an example of the inadequate use of natural stone materials in the cladding of a façade. In this case, limestone is used in a maritime environment, in a building about 300 m from the sea, resulting in salt crystallisation on the surface and wear associated with erosion. The functional classification of claddings during the design stage would have been a useful tool to guide the specification of this material. That would also have been helpful in the case in Figure 8b, where scratches and wear of the finishing coat occur on a wood flooring. Probably due to situations mostly like this one, the identification of “C-B7 Use of unprescribed, inadequate, incompatible, low-quality, non-certified and/or non-approved materials” in wood floorings is also frequent (42% of defects are associated with this cause).



Figure 8. Signs of use of unprescribed, inadequate, incompatible, low-quality, non-certified and/or non-approved materials: (a) in a natural stone cladding in a maritime environment; (b) in a wood flooring.

Cause C-B7 also has a high average frequency of identification within the 12 building elements/materials. In external claddings of pitched roofs, natural stone claddings, painted façades, door and window frames and wood floorings, this defect is identified as a cause of more than 10% of the defects. In general terms, the low quality of building materials is appointed as the main cause of building collapse [71], and one of the main causes of high maintenance cost [72]. The sensitiveness of natural stone to environmental conditions and application specificities, combined with carelessness while prescribing this type of material and focusing more on aesthetics than on other properties, are the probable reasons for the higher prevalence of such a cause in natural stone claddings. Amaral et al. [73] highlight that inadequate material selection of ornamental stones is a very common cause of defects. Lopez-Arce et al. [74], while studying the extensive degradation at Bonaval Monastery in Spain, concluded that the extensive salt weathering resulted from the use of sulphate-bearing mortars combined with magnesium in the dolomite stone, magnesite of the plaster mortar and

Mg-rich aggregate embedded in the bedding mortar, highlighting the importance of compatibility between materials.

On the other hand, cause “C-C9 Accidental collisions with the cladding” is the one directly correlated with defects in most types of building elements/materials (10 out of 12). The only building materials/elements in which it is not a near cause of the occurrence of defects are the external claddings of pitched roofs and painted façades. In the others, it is mostly associated with defects “A-C6 Scratches/grooves and deep wear”, “A-C8 Material gap/puncture” and “A-C2 Oriented cracking on the current surface”. Macarulla et al. [69] also identified surface appearance defects, namely hits/scratches as the result of a collision (or abrasion). In wood floorings, the cause–effect relationship between collisions and scratches additionally depends on wood hardness, reflecting the ability of wood to resist the penetration of objects into its structure [75].

An example of deep wear in a wall render is represented in Figure 9a, where the hard manoeuvring of a vehicle resulted in a collision with the wall (C-C9) and subsequent loss of a part of the render. Furthermore, in door and window frames, accidental collisions (C-C9) are a direct cause of “A-C3 Fracture or splintering on the current surface”. In Figure 9b, an example of a defect is illustrated, where the collision of a small stone while the adjacent land was being ploughed, resulted in the fracture and piercing of the glass pane.

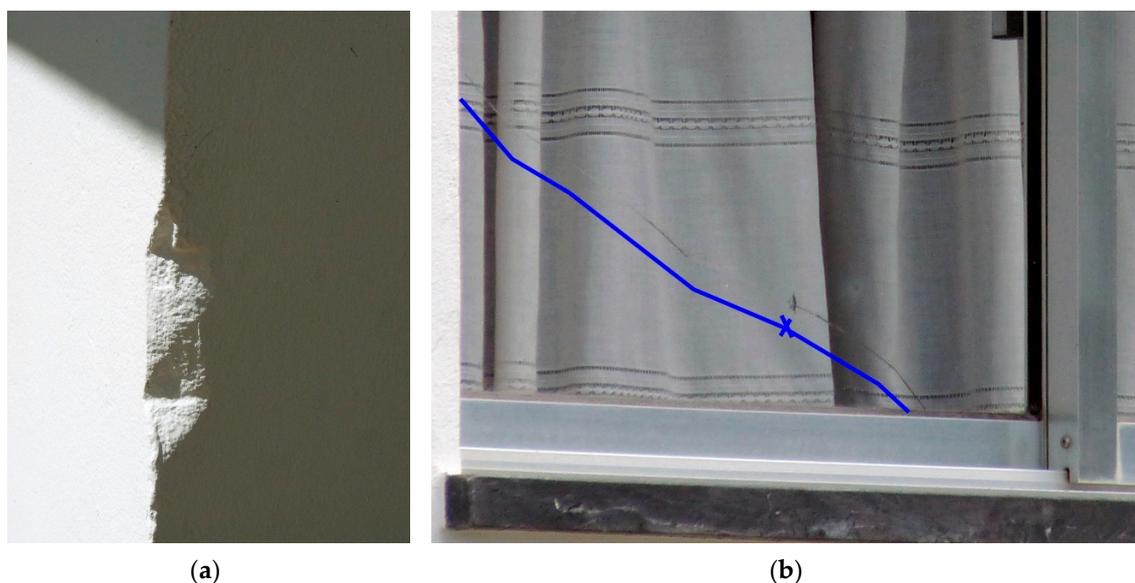


Figure 9. Results of accidental collisions with the cladding in (a) a wall render and (b) the glazing of a window.

Summing up, there is a relatively balanced distribution of frequent causes of defects by category, i.e., root causes, with a slight prevalence of execution errors. Alencastro et al. [76] listed five types of defects affecting the quality of construction projects, one of which being “incorrect installation”. As for causes, they can be associated with changes, errors, omissions or damage, and the most common sources of defects in construction projects are workmanship, design, management, machinery, material or lack of protection of already installed items. Additionally, defects associated with implementation or workmanship at the construction stage may affect thermal performance in terms of thermal bridging, air permeability, discontinuity of the insulation layer, and gaps in vapour and air barriers. Josephson and Hammarlund [25] attribute 35–55% of the total defect cost during the construction stage to defects resulting from execution issues, while, at the maintenance and operation stage of the building life cycle, execution errors represent 20–45% of total defect costs.

As for the direct relationship with defects, environmental actions are those that can contribute more to the final stages of the degradation process. Building elements and materials are expected to

degrade over time due to exposure conditions. Environmental aggressive agents are one of the main factors associated with degradation of the building envelope, as it plays a protective role, guarding the building against those same agents [77].

5. Conclusions

The research presented in this paper tries to answer “how can a classification list of causes applicable to the whole building be achieved?” In doing so, the study provides a comprehensive classification list of the causes of defects for the non-structural elements of the building envelope, explaining how it was achieved. Such a list is included in a global inspection system for building envelopes, but may also be used outside of its scope as an auxiliary tool for surveyors while diagnosing pathological phenomena. The analyses presented support the adequacy of the proposed classification, showing results about the most common causes of defects. Only by knowing and understanding the origin of pathological phenomena can defects be prevented and their reoccurrence eliminated.

Some research on building pathology presents studies referring not only to defects but also to their causes. However, those studies usually focus more on classifying defects than on extensively listing causes, which are frequently few and associated with general concepts, more related to the origin of the cause than to the cause itself (e.g., stating the cause as being a design error). The proposed classification list, although long, provides specific causes applicable to twelve types of building elements/materials, instead of providing causes only specific to a partial building context (e.g., causes of defects in timber building elements). So, the paper shows a possible way of developing a classification of causes applicable to several building elements/materials.

Future works in this field should involve the development of a computer tool for inspecting buildings implementing the IST-UL’s global inspection system. That tool will ease the collection of fieldwork data, which may be used for a faster production of information on building pathologies of the building envelope. Additionally, the management of maintenance actions based on the defect–cause relationship should be further studied, based on quantitative data, as well as preventive measures at the design and construction stages.

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