INTERRELATIONS BETWEEN THE TYPES OF DAMAGES AND THEIR ORIGINAL CAUSES IN THE ENVELOPE OF BUILDINGS

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ABSTRACT

The envelope is the skin that covers buildings and protects them from weather and outdoor actions. Consequently, this envelope is prone to have many deficiencies. This paper analyses 2,030 cases that correspond to current Spanish buildings, from which the pathology combinations are categorised. In other words, each case studied is associated and quantified with the type of existing damage, the construction unit in which the damage occurred, and its original cause, thus showing the most recurrent and dominant combination and the construction typology where pathology combinations took place. A total of 10 groups of pathology combinations were determined in the horizontal envelope, and 34 groups in the vertical envelope. The results could be useful for technicians to have a very significant view of the most troubled points of envelopes, so preventive measures can be adopted when writing the project (design phase) and performing construction works. In this manner, damages would be reduced in the building envelope, as well as use costs, and habitability conditions would be improved, thus contributing to the most sustainable behaviour of the building process.

KEYWORDS

Deficiencies, facades, windows, roofs, typologies

HIGHLIGHTS

-A total of 5 construction units, 20 types of damages, and 33 types of original causes have been identified.
-Each case (2,030 in total) is associated with 4 building typologies.
-A total of 228 different pathology combinations are characterized.
-The most frequent, recurrent and dominant combinations are determined.
- A legal data source, without precedents in forensic engineering, has been used.

1. INTRODUCTION

1.1. General framework

The building envelope is composed by the construction elements that separate the interior from the exterior and therefore is responsible for most features of building habitability conditions. In this manner, there are many related aspects when analysing the damages of the parts of an envelope (Bauer et al. 2014, Conceição et al. 2019).

In general, damages in building is an issue discussed in research studies, but the discussion is usually focused on specific case studies and construction elements. However, the pathology parameters that influence these elements are not developed in certain research studies (Olanrewaju et al. 2010) because of the great difficulty of obtaining broad datasets related to building damages (Gaspar and de Brito 2005).

According to *Andújar-Montoya et al.* (Andújar-Montoya et al. 2017), the main reasons of the problems in buildings are related to the design phase and the execution phase, representing most deficiencies that occur later. Other authors postulated that it is possible to remove latent deficiencies through a very thorough design (Chong and Low 2006). From this point of view, *Al-Sharif et al.* (Al-Sharif et al. 2015) indicated that a building could be considered comfortable when sufficient technical features were included in a project (not just those required by the regulation, but those required by users). Other research studies have also considered appropriate maintenance as an essential part of the operation quality (Lee et al. 2016) and absence of problems in the building (Filippín and Flores Larsen 2005).

In addition, the study of building damages is inevitably related to the repercussion on costs. Certain research studies have stated that processes to repair defective works increase the project cost by 52% (Love 2002), considering that the economic value of repairs is generally determined by both the optimization of resources and the possible deficiencies and omissions (Alba Cruz et al. 2013). To mitigate this situation and to reduce damages, some research studies have considered obtaining a quality management system for the design process (Alba Cruz et al. 2013) or the use of avant-garde technologies in processes (Pauwels 2014), such as the Building Information Modelling (BIM) technology (The American Institute of Architects 2013). This reduction would not be only verified in the design phase (in which this technology has already been used) but also in the phases of construction (Chou et al. 2009) and use, which are still a long way to go (Ministerio de Fomento 2015). To reduce periods of time and other problems from the construction deficiencies, voluntary and non-judicialized procedures could be employed (Koh et al. 2017) to solve more quickly and in a less traumatic way the possible conflicts with clients through an independent arbitrator's decision (Rodríguez de la Flor 2015).

Nevertheless, the experience on the repercussion of certain types of damages and their repairs could be positive by using it as a learning (Love et al. 2018) and improvement opportunity for the future (Mills et al. 2009).

1.2. Antecedents from other research studies

As this research is focused on the scope of the envelope and construction units in particular, such as roofs, facades and windows (Park and Song 2018), the deficiencies and rework processes are significantly related to humidity (Pereira et al. 2018), rainfalls (Olsson 2018), the entry of water through various junctions and troubled points (Boudreaux et al. 2018) or the disposition of waterproofing (Walter et al. 2005). Claddings have also a key role in envelopes (Sá et al. 2015) and are involved in their pathology processes (Garcez et al. 2012). *Azhar* (Azhar 2011) determined that the existing deficiencies in the claddings of various buildings increase if quality control (of materials and execution) is not rigorously monitored. For this reason, an analysis process and a previous control of the technical construction specifications of the requirements of facades (Carretero-Ayuso et al. 2018) and roofs (Carretero-Ayuso et al. 2016) could significantly reduce the number of possible damages in the use phase.

Historically, roofs are among the construction elements most prone to have problems (Conceição et al. 2017), according to old construction treaties (Ger Lobez 1898). All the possible deficiencies in roofs are not pathological (damage existence), but some can be catastrophic (Piskoty et al. 2013). Scientific references on roofs are usually focused on both the analysis of constituent materials and their application (Misar and Novotný 2017) and the study of certain typologies (Liu et al. 2019), such as green roofs (Feitosa and Wilkinson 2020). They are also focused on the mechanical behaviour of the junctions between waterproofing pieces (Gonçalves et al. 2008), the action of the suctions generated by wind (Silva et al. 2010), the junctions subjected to artificial weather (Gonçalves et al. 2011) or the way of placing the bindings between sheets (Ko et al. 2006).

Regarding facades, some research studies are also focused on materials, and the design errors are responsible for 60% of damages in facades (Silvestre and de Brito 2011). A reason for this high percentage is the difficulty of providing a general typology of facade (Molnár and Ivanov 2016) that includes an ideal solution from a construction point of view (Hradil et al. 2014). Other reasons why facades are prone to problems are the many elements that constitute facades (Carraro and Oliveira 2015) and the variability of the construction systems available (Gaspar et al. 2016).

On the other hand, when diagnosing an existing damage, its original causes are usually repeated in the current working process of other buildings, so these cases should be disseminated to improve the building sector (Meiss and Muñoz 2015). This situation also takes place in other countries, where facades and roofs generate most building problems (Ilozor et al. 2004), as in Spain. For this reason, knowing the recurrence percentages of the most common deficiencies is determinant to know the weaknesses and is a first step to obtain minimum quality results in future buildings (Lee et al. 2016).

1.3. Goals of this study

In this sense, the statistical assessment of complaints and the analysis of deficiencies could be useful to study in detail what is happening today in the building sector and to know what type of deficiencies are the most common in a given country (Sarman et al. 2015). This paper aims to responding these issues related to the envelope of current buildings built in Spain.

For this purpose, more than two thousand cases have been used in this study. This number is greater than those taken as a basis in most engineering research studies, according to the analysis of the scientific literature from the last two decades. Moreover, there are no research studies based on a source of data and a methodology with the same characteristics as those developed in this paper. In addition, the amount of data used corresponds to Spain as a whole and covers all the cases to be analysed.

In other studies, most occasions belong to the same construction or property development company, with a reduced number of cases, or belong to surveys based on them. In this paper there is no parameter that links cases, thus guaranteeing the independence of the results obtained.

2. METHODOLOGY

2.1. Study origin

A series of construction terms could be quantitatively classified in various ways. For instance, according to their functional character (Georgiou et al. 1999) or the building period when they were built (Macarulla et al. 2013) or developing an ad hoc method (Silvestre and de Brito 2010). This research carries out an inductive classification of our own. However, the conceptual classification is supported by its similarity with a significant Spanish research conducted in the last third of the 20th century on some construction elements (Vieitez Chamosa and Ramírez Ortiz 1984).

The methodology consisted of acquiring data from the expert's reports on liability insurances of technical architects and building engineers in Spain (Musaat 2015). The reports selected were those which initiated dossiers of cases based on the users/owners' complaint related to the existence of construction damages in their buildings. These data were acquired from the dossiers meeting the condition of having a definitive court's decision, belonging to the dossiers initiated between 2013 and 2015 (Serjuteca 2015). It took several years to make these complaints, to file a lawsuit, to have a judgement, to turn these judge's decisions into high judicial instances, and eventually to give a definitive and unappealable judgement. Only at this point the records were part of the research: they were read, analysed, classified, and assessed.

2.2. Descriptors used

A total of 2,030 cases have been considered in this study. All belong to the outdoor building envelope: 1,229 cases belong to the vertical envelope, and the remaining cases (801) belong to the horizontal envelope. In addition, many parameters have been included, thus enriching the study but making it more complex:

-Base parameters: Composed by joining three 'descriptors', which are described above. These parameters are required to identify a case: location/damage/original cause. There are 58 different concepts in them (Table 1).

-Complementary parameters: Composed by other aspects that characterize the dataset studied, either additionally (building typology= 4 building formats) or based on the interrelation among the 'descriptors' mentioned (different pathology combinations= 228 types).

Table 1 – Codification and relation of the descriptors used in the research

DESCRIPTOR	CODE	CONCEPT
Descriptor 1: Construction units	**Code U**	**Name of the construction unit**
	U1	Window frameworks
	U2	Pitched roofs
	U3	Flat roofs
	U4	Uncoated facades
	U5	Coated facades
Descriptor 2: Types of damages	**Code D**	**Name of the damage**
	D1	Biological attack
	D2	Spalling and chipped parts
	D3	Thermal anomalies
	D4	Efflorescence
	D5	Wind entry
	D6	Direct infiltrations of water and/or dripping
	D7	Cracks in the central part of wall sections
	D8	Cracks in the finishing coats
	D9	Cracks in the perimeter parapets of the roof
	D10	Cracks in the lateral side walls of the roof (gables)
	D11	Horizontal cracks in slab fronts
	D12	Vertical cracks in pillar alignments
	D13	Detachments in corners (junctions between walls sections)
	D14	Detachments in structural patching
	D15	Condensation humidity
	D16	Capillary humidity
	D17	Infiltration humidity
	D18	Absence of planimetry
	D19	Breakage of pieces or elements
	D20	Others/no data
Descriptor 3: Types of original causes of damages	**Code C**	**Name of the original cause**
	C1	Continuous presence of humidity
	C2	Absence or deficiency of adherence to the substrate
	C3	Absence or deficiency of anti-drip groove, gutter or drainpipes
	C4	Absence or deficiency of sealing
	C5	Absence or deficient execution of singular elements
	C6	Absence of waterproofing
	C7	Absence of barrier against capillary humidity
	C8	Deficient disposition of waterproofing sheet
	C9	Deficient disposition of tiles
	C10	Absence or inappropriate ventilation of the air gap of the roof
	C11	Incorrect disposition of the thermal insulation
	C12	Absence or deficiency of construction junctions
	C13	Absence or deficiency of patching in structural elements
	C14	Inappropriate or badly placed lintels
	C15	Direct contact with the ground
	C16	Defect or absence of verticality
	C17	Defects in the fixing of windows
	C18	Deficient support base of brick wall sections
	C19	Deficient quality of cement claddings
	C20	Deficient treatment of wood

	C21	Deficient junction with roof bowls and drains
	C22	Bad junction with the salient elements of the facade
	C23	Existence of thermal bridges
	C24	Absence or deficient junction with vertical surfaces
	C25	Absence of individual junctions between pieces (butt-joint installation)
	C26	Inappropriate or deficient material
	C27	Presence of expansion movements not considered
	C28	Inappropriate slope of the roof element
	C29	Presence of phreatic level not considered
	C30	Absence of protection of the punching of the waterproofing sheet
	C31	Inappropriate anchorage or fastening system
	C32	Insufficient assembly between brick walls or interrupted built joints
	C33	Unknown cause or without diagnosis

The analysed reports correspond to 100% of those in Spain in the period mentioned. This research is not a characteristic sample whose statistical representation should be verified because all the damages of the envelope proved in the study period are included (therefore, there is no uncertainty as it is not a partial sample). It is a general census of the pathological cases in Spain.

That circumstance, along with the complexity to obtain this type of data, implies that this research has no precedents because of both the number of cases analysed and the origin of the source of data.

As previously mentioned, each case to be studied is characterized by 3 descriptors:

- Descriptor 1 (construction unit). This element is where the problem or deficiency is. This descriptor is described in the upper section of Table 1. There are 5 construction units that belong to the building envelope.
- Descriptor 2 (type of damage). It is the problem or deficiency itself. The 20 types indicated in the central section of Table 1 have been characterized according to the determination of the experts who made the reports of each case.
- Descriptor 3 (type of original cause). It is the reason why a problem or deficiency arises. The 33 types indicated in the lower section of Table 1 have been typified also according to the experts who visited the buildings of each case.

Apart from these 3 descriptors, another aspect has also been considered to provide the cases with greater concision and characterization: the building typology. According to this criterion, each case is assigned to a ‘building block’, an ‘isolated single-family’, a ‘semi-detached single-family’, and a ‘non-residential buildings’.

2.3. Scope of the data source

Based on the previous mention, the damages and original causes included in Table 1 were not selected by the authors. They are the result of compiling all the existing cases that were demanded by users/owners and verified by experts (i.e. it is not a list beforehand).

Thus, damages are initially detected by users/owners, and then the experts verify and analyse them according to each situation. Under the consideration of each expert, there will be damages that could be sometimes characterized just by the visual observation, and others that require certain instruments or tests (e.g. hygrometers, thermography, etc.).

Consequently, the analysed records are usually treated differently with respect to the construction characteristics, so certain properties of the elements are usually unknown. This is the case of the materials used, which are not deeply addressed in all the cases. There are even records not mentioning them, such as in certain demands where the original cause of the damage is more related to the bad design or execution (inappropriate slope, absence or deficiency of sealing, etc.), thus not considering the nature of the materials used.

This study is therefore configured by using a starting database, so the analysis is focused on the descriptors which could be extracted: damages, original causes and the construction units affected. After classifying the construction units, it is verified that the materials used for each construction unit are very homogeneous and the typologies are very common among them because building solutions in Spain are significantly standardised.

2.4. Cluster analysis

As mentioned above, this research is not based on a sample but on the total of the existing cases, so a statistical assessment was carried out by analysing the grouping of descriptors. For this purpose, the k-means algorithm, which is based on the centroid concept, has been used (Hartigan and Wong 1979). The algorithm begins with a set X of n individuals which are classified into k clusters, for which a W partition of that set with $W = (w_1, \dots, w_a, \dots, w_b, \dots, w_k)$ is considered, so $\left(\bigcup_{a=1}^{k} w_a = X, w_a \cap w_b = \emptyset, \mathrm{a} \neq \mathrm{b}\right)$, thus the total sum of the sums of squares of the Euclidean distances within each cluster is minimum (Eq. 1).

$$\underset{W}{\operatorname{argmin}} \sum_{a=1}^{k} \sum_{x_i \in w_a} \sum_{r=1}^{p} (x_{ir} - \mu_{ar})^2 \qquad (1)$$

The performance of k-means depends on the number of clusters: the larger the number of clusters, the smaller the variation (i.e., more individual clusters are created, thus losing the main potential of the analysis that is the detection of similarity patterns among individuals). The number of clusters was optimally selected with the silhouette index ($s(i)$) and the ratio between the sum of squares and the total sum of square (BSS/TSS).

Therefore, $s(i)$ analyses the similarity of an individual with the remaining individuals of a same cluster (Eq. 2). $s(i)$ could obtain values between -1 and 1. The meaning of these values determines the suitability of the cluster analysis: (i) if the value is between 0 and 1, the observation is well grouped, obtaining optimal values those closer to 1; (ii) if the value is 0, the individual is between two clusters. This could mean that either the individual shows very different characteristics from the remaining that are not grouped with the others or that the analysis has excessively classified individual clusters; and (iii) if the value is between -1 and 0, the individual is in the incorrect cluster.

$$s(i) = \frac{b(i) - a(i)}{max\{a(i), b(i)\}} \qquad (2)$$

Where $b(i)$ is the minimum average distance between the individual and the other clusters, and $a(i)$ is the average distance between the individual (i) and the other points of the same cluster.

Finally, the BSS/TSS ratio is a relationship of the compactness of the cluster (Eq. 3). It is a percentage relationship that can obtain values between 0 and 100%. The greater the value of the ration, the greater the compactness of the individuals within a cluster. Likewise, given that TSS=BSS+WSS, if BSS is greater, WSS is lower.

$$\frac{BSS}{TSS} = \frac{\sum_{k=1}^{K} \sum_{j=1}^{p} \left(\bar{x}_{kj} - \bar{x}_G\right)^2}{\sum_{k=1}^{K} \sum_{j=1}^{p} \left(\bar{x}_{kj} - \bar{x}_G\right)^2 + \sum_{k=1}^{K} \sum_{i \in S_k} \sum_{j=1}^{p} \left(x_{ij} - \bar{x}_{kj}\right)^2} \qquad (3)$$

Where $\bar{x}_G$ is the grand mean of the means of each cluster.

3. RESULTS

The classifications and groups developed is the combination of the results obtained in the research, together with the several concepts obtained from the authors' experience. During the years, a series of patterns have been proved in the studies on constructive pathologies, including observing that the descriptors are usually grouped in three or four large groups (the designations of each group –cluster– are included below).

3.1. Individual results per descriptor

The relative frequency of each pathology descriptor was determined.

Descriptor 1 analysed the existing construction units. According to Figure 1, the coated facades was where the number of cases was greater (U5=29.75%), followed by flat roofs (U3=27.09%) and window frameworks (U1=16.80%).

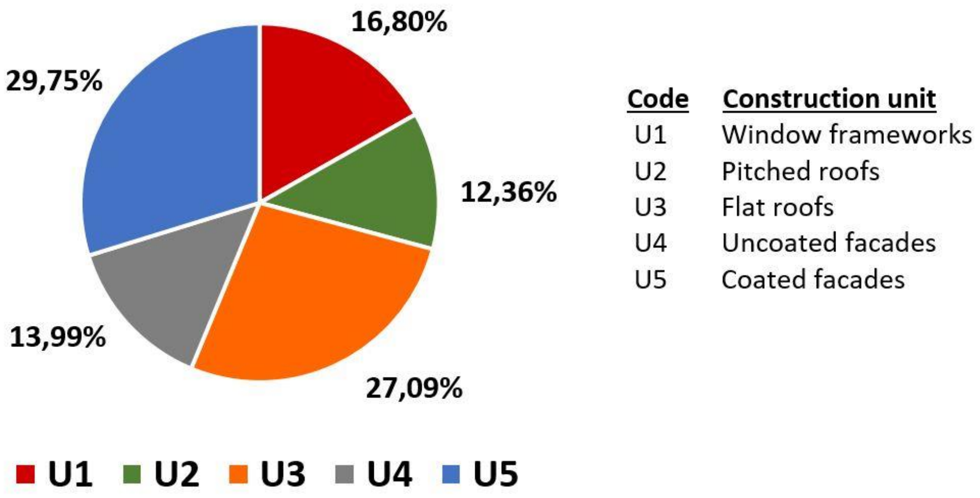

Figure 1 – Percentage of cases per construction unit

To show the results of the descriptor 2 indicated in Table 1 (type of damage), the diagram of accumulated percentages was drawn and included in Figure 2. For this purpose, the unidimensional cluster analysis was previously conducted to determine the existing groups between the percentage impact and the type of damage (Figure 3). There were 4 clusters according to the importance of the type of damage. The suitability of this classification was reflected in the value obtained with $\frac{BSS}{TSS}$ (99.5%) and $s(i)$ (0.73). There was an individual cluster for D17, and partial groups between 2 and 9 types of damages for the others: 'cluster 1' with 8 damages, 'cluster 2' with 9 damages, and 'cluster 4' with 2 damages. Nonetheless, the clusters detected with the analysis were not arranged by the percentage value due to the own characteristics of the algorithm. This could be seen through the centroid of each cluster: 3.33% ('cluster 1'), 0.77% ('cluster 2'), 33.35% ('cluster 3'), and 12.58% ('cluster 4'). Thus, the centroid of the clusters did not present an ascending tendency because of their organisation in the analysis. The clusters were therefore organised as follows: clusters 3 and 4 corresponded to the first category of damages (distinguishing two subcategories by each cluster), cluster 1 corresponded to the second category of damages, and cluster 2 corresponded to the third category of damages.

Analysing constructively the results from Figure 2, it can be observed that the most present type of damage was 'infiltration humidity', which occurred in more than one-third of the total percentage (D17=33.35%), then 'direct infiltrations of water and/or dripping' (D6=17.54%), and finally 'condensation humidity' (D15=15.62%). From these three types of damages (called 'primary'), the percentages hugely decreased because only their sum covered the two-thirds of the total of cases (66.51% of the total), thus obtaining a Pareto relationship ~16-67.

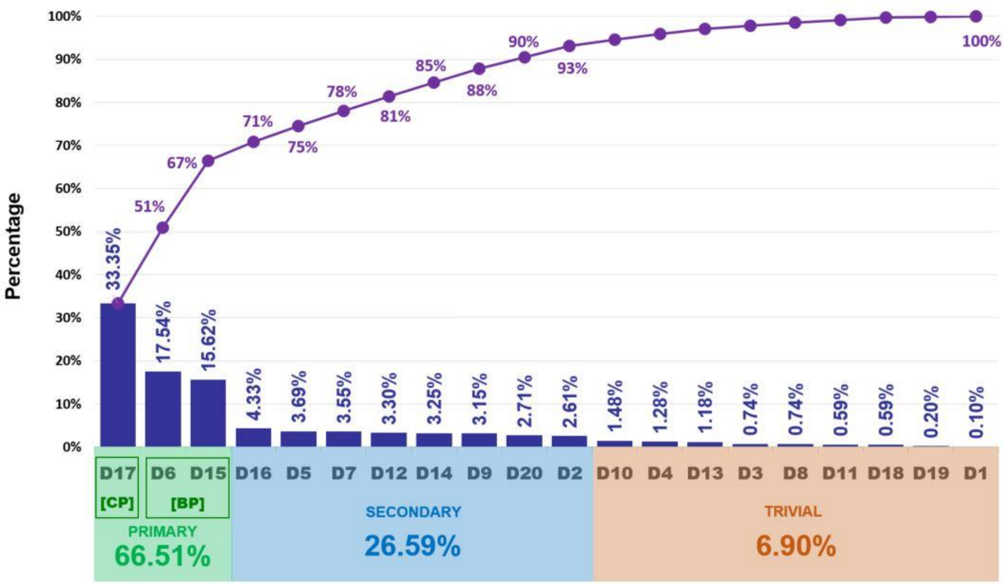

Figure 2 – Percentages of cases obtained according to the type of damage and sum of the percentage values of each category.

There was an internal asymmetry in the percentage obtained by these three first damages (according to the cluster analysis conducted), as the second and third position summed the equivalent of that obtained by the first position. For this reason, the subcategory D6 and D15 (=33.16%) was called 'basic primary [BP], and the first damage (D17=33.35%) was called 'critical primary [CP] because of the high individual concentration of cases (Figure 2).

On the other hand, there were a series of damages with an intermediate presence ('secondary' damages: D16+D5+D7+D12+D14+D9+D20+D2) that were between 2% and 15% and all together summed 26.59% of the total (belonging to cluster 1). Finally, there were 9 types of damages with marginal presence ('trivial damages': cluster 2), whose individual presence percentage was lower than 2% (see the terminology section at the end of this paper).

Figure 4 is included to show the values obtained in the descriptor 3 defined in Table 1 (types of original causes); this figure shows a decreasing order of the presence percentages of this descriptor. The most prevalent original causes were 'absence or deficiency of sealing' (C4=14.38%) and 'deficient disposition of waterproofing sheet' (C8=9.01%), which have a construction relationship with the types of damages showed in Figure 2.

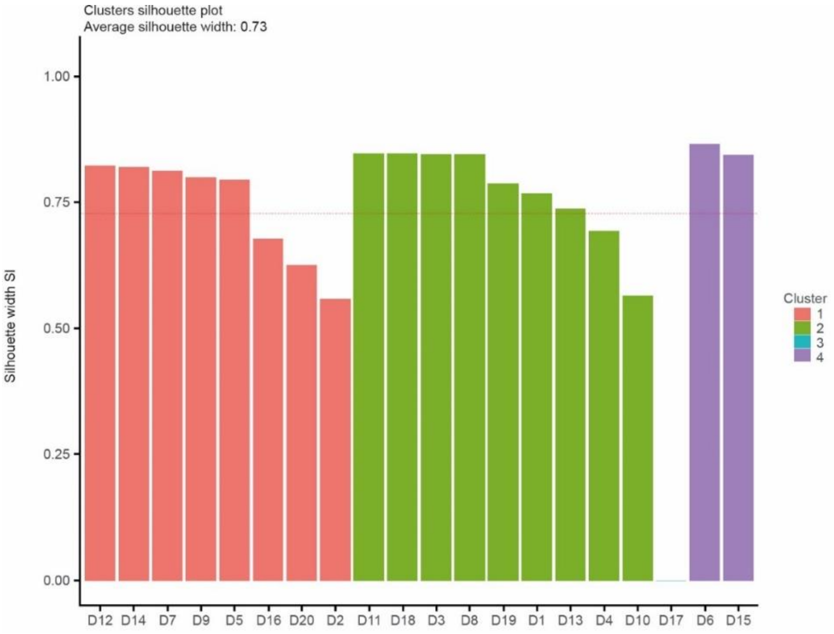

Figure 3 – Distribution of the silhouette in each type of damage after conducting the cluster analysis.

According to the presence of each original cause, four collections were created (according to the percentage similarity and the cluster analysis also conducted in this descriptor), as Figure 4 shows (read also the definitions included at the end of this paper, in the terminology section). In this manner, C4 was called 'hyper-common', and C8+C23+C11+C13 were called 'usual'.

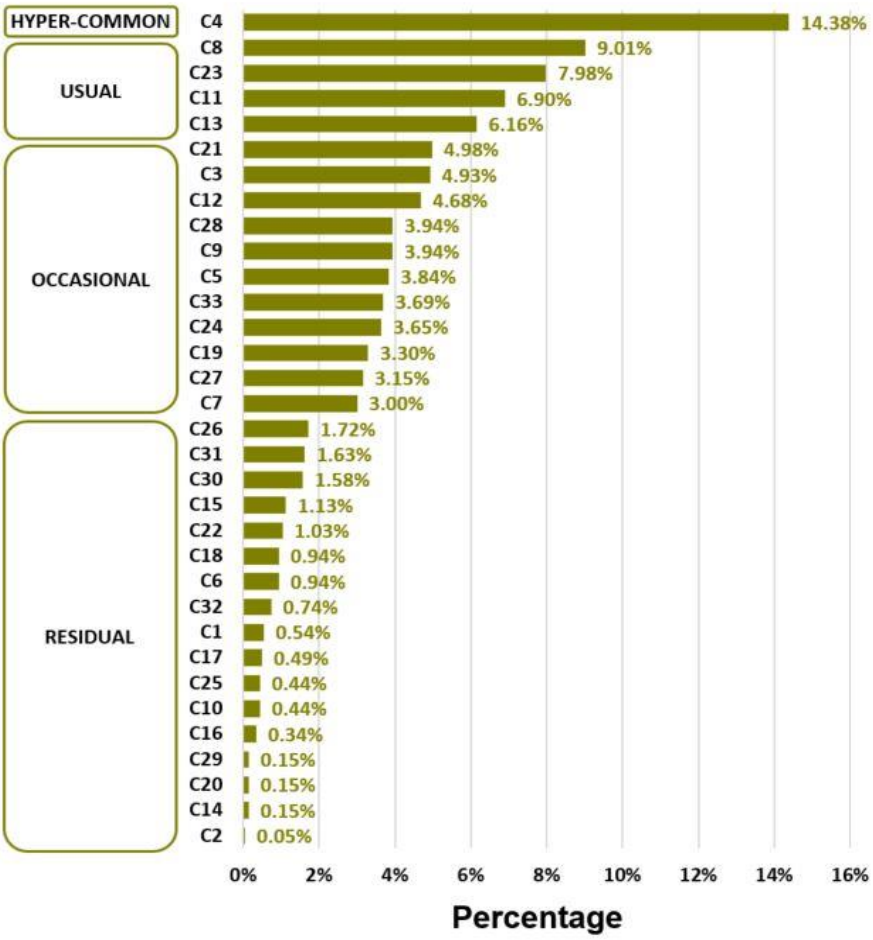

Figure 4 – Percentages of cases obtained according to each original cause

3.2. Results per construction unit and type of damage

Figure 5 shows the relationship between the type of damage (descriptor 2 from Table 1) and the construction unit in which they occurred (descriptor 1 from Table 1) to precisely know which damages are involved in each place and to have detailed information to be used later in the prevention during the design stage.

Following a combined nomenclature based on Table 1, the damages with a greater percentage in comparison with the total of the study were $D6_{U3}$=12.41%, $D17_{U3}$=9.75%, $D17_{U1}$=8.42%, $D17_{U5}$=8.33%, and $D15_{U1}$=6.06%. Thus, the 'infiltration humidity' (D17) was on the top in 3 out of these 5 times.

Furthermore, the types of damage D6, D15, D17, and D20 were present in the two types of roof (U2 and U3). As for the two variants of facades (U4 and U5), the same types of damage were repeated, except D19 (breakage of pieces or elements) which only occurred in the uncoated facades. Finally, the types of damage which were common in the 5 construction units were 'condensation humidity' (D15) and 'infiltration humidity' (D17), and again the key role of humidity in the study was notable.

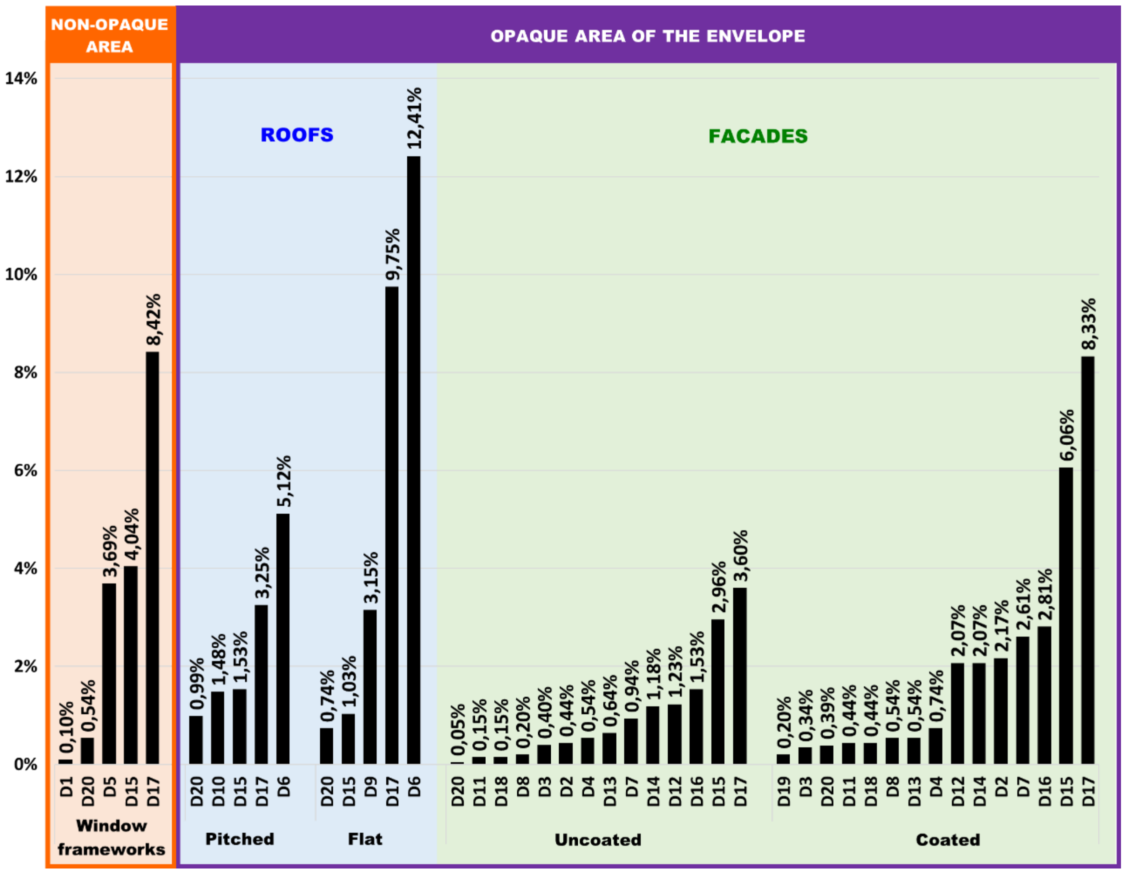

Figure 5 – Distribution of the damages in each construction unit

3.3. Results per pathology combinations

A pathological combination is the construction interrelation among the 3 descriptors (construction unit/damage/original cause); that is, the types of damages within a construction element, their specific original cause, and the frequency of those cases.

This study verified 228 types of pathology combinations (developed in Table 2 and Table 3). Among them, 70 were in roofs (U2+U3) –the horizontal envelope– and 158 were in facades and window frameworks (U1+U4+U5) –the vertical envelope–. Thus, the number of pathology combinations is the sum of the number of rows by construction unit in these tables, and the cases correspond to the values indicated in the 'subtotal' column. Data are quantified at the end of the tables.

The pathology combinations for the construction units of the horizontal envelope (see Table 2) were as follows: in the pitched roofs (U2), there were 5 'groups of pathology combinations' *(those sharing the same damage in a construction given unit: number of cells of the 'damage column' in that table)* and 36 different types of pathology combinations. The most numerous group was that due to 'direct infiltrations of water and/or dripping' (D6=104 cases) followed by the group of 'infiltration humidity' (D17=66 cases). As for flat roofs (U3), there were 5 'groups of pathology combinations' and 34 different types of pathology combinations. In this construction unit, the most numerous group was that due to 'direct infiltrations of water and/or dripping' (D6=252 cases) followed by the group of 'infiltration humidity' (D17=198 cases).

Table 2 – Relation and quantification of the pathology combinations in the horizontal envelope

INTERRELATION CONSTRUCTION UNIT / DAMAGE / ORIGINAL CAUSE IN ROOFS

Pitched roofs - U2			
Damage	**Cause**	**Number**	**Subtotal**
D6	C4	1	104
	C5	28	
	C8	5	
	C9	45	
	C21	5	
	C24	12	
	C27	1	
	C28	6	
	C33	1	
D10	C5	6	30
	C10	5	
	C12	3	
	C24	1	
	C27	15	
D15	C5	1	31
	C8	2	
	C9	3	
	C10	4	
	C11	19	
	C27	1	
	C33	1	
D17	C4	3	66
	C5	12	
	C8	2	
	C9	25	
	C11	1	
	C12	1	
	C24	3	
	C27	2	
	C28	16	
	C33	1	
D20	C5	7	20
	C9	7	
	C11	2	
	C27	1	
	C28	3	

Flat roofs - U3			
Damage	**Cause**	**Number**	**Subtotal**
D6	C4	14	252
	C5	8	
	C8	93	
	C12	2	
	C21	71	
	C24	38	
	C27	4	
	C28	6	
	C30	16	
D9	C4	1	64
	C5	2	
	C12	22	
	C21	1	
	C24	1	
	C27	37	
D15	C4	1	21
	C8	3	
	C11	16	
	C24	1	
D17	C4	6	198
	C5	12	
	C8	78	
	C12	1	
	C21	21	
	C24	18	
	C27	2	
	C28	44	
	C30	16	
D20	C4	2	15
	C5	2	
	C12	2	
	C21	3	
	C27	1	
	C28	5	

DATA QUANTIFICATION IN U2
Number of groups of pathology combinations in U2: 5
No of pathology combinations in U2: 36
Number of cases in this construction unit: 251

DATA QUANTIFICATION IN U3
Number of groups of pathology combinations in U3: 5
No of pathology combinations in U3: 34
Number of cases in this construction unit: 550

Table 3 – Relation and quantification of the pathology combinations in the vertical envelope

INTERRELATION CONSTRUCTION UNIT / DAMAGE / ORIGINAL CAUSE IN FACADES AND WINDOW FRAMEWORKS

Window frameworks - U1			
Damage	Cause	Number	Subtotal
D1	C20	1	2
	C33	1	
D5	C4	49	75
	C20	1	
	C26	7	
	C33	18	
D15	C4	6	82
	C23	69	
	C26	2	
	C33	5	
D17	C4	146	171
	C20	1	
	C26	2	
	C33	22	
D20	C4	2	11
	C26	1	
	C33	8	

DATA QUANTIFICATION IN U1
Number of groups of pathology combinations in U1: 5
Number of pathology combinations in U1: 17
Number of cases in this construction unit: 341

Uncoated facades - U4			
Damage	Cause	Number	Subtotal
D2	C1	1	9
	C3	1	
	C12	3	
	C26	2	
	C31	2	
D3	C11	7	8
	C31	1	
D4	C1	2	11
	C3	4	
	C19	1	
	C26	3	
	C33	1	
D7	C12	7	19
	C13	1	
	C18	3	
	C19	3	
	C25	1	
	C26	3	
	C32	1	
D8	C18	2	4
	C32	1	
	C33	1	
D11	C18	1	3
	C32	2	
D12	C4	2	25
	C12	12	
	C13	4	
	C18	3	
	C32	4	
D13	C12	3	13
	C13	8	
	C32	1	
	C33	1	
D14	C1	1	24
	C12	4	
	C13	18	
	C33	1	
D15	C11	37	60
	C23	21	
	C26	1	
	C33	1	
D16	C7	23	31
	C15	6	
	C29	2	
D17	C1	2	73
	C3	26	
	C4	11	
	C6	5	
	C13	16	
	C15	1	
	C19	1	
	C22	7	
	C33	4	
D18	C16	3	3
D20	C3	1	1

DATA QUANTIFICATION IN U4
Number of groups of pathology combinations in U4: 14
Number of pathology combinations in U4: 55
Number of cases in this construction unit: 284

Coated facades - U5			
Damage	Cause	Number	Subtotal
D2	C1	1	44
	C4	3	
	C18	1	
	C19	6	
	C25	3	
	C26	7	
	C31	23	
D3	C11	7	7
D4	C3	8	15
	C19	5	
	C26	1	
	C33	1	
D7	C1	1	53
	C2	1	
	C4	2	
	C12	6	
	C13	1	
	C18	3	
	C19	35	
	C25	1	
	C26	1	
	C31	1	
	C32	1	
D8	C14	2	11
	C17	8	
	C18	1	
D11	C12	4	9
	C13	2	
	C14	1	
	C18	1	
	C25	1	
D12	C4	5	42
	C12	18	
	C13	3	
	C17	1	
	C19	5	
	C22	2	
	C26	1	
	C32	5	
	C33	2	
D13	C12	1	11
	C13	6	
	C18	1	
	C25	1	
	C26	1	
	C33	1	
D14	C12	4	42
	C13	31	
	C18	2	
	C19	3	
	C31	1	
	C33	1	
D15	C1	1	123
	C11	49	
	C19	2	
	C23	71	
D16	C4	1	57
	C7	38	
	C15	16	
	C29	1	
	C33	1	
D17	C1	2	169
	C3	59	
	C4	37	
	C6	14	
	C13	35	

	C17	1	
	C19	2	
	C22	12	
	C25	1	
	C26	1	
	C31	3	
	C33	2	
D18	C16	4	9
	C18	1	
	C19	3	
	C26	1	
D19	C25	1	4
	C26	1	
	C31	2	
D20	C3	1	8
	C11	2	
	C12	2	
	C19	1	
	C23	1	
	C33	1	

DATA QUANTIFICATION IN U5
Number of groups of pathology combinations in U5: 15
Number of pathology combinations in U5: 86
Number of cases in this construction unit: 604

The pathology combinations for the construction units of the vertical envelope (see Table 3) were as follows: in window frameworks (U1), there were 5 ‘groups of pathology combinations’ and 17 different types of pathology combinations. The most numerous group was that due to ‘infiltration humidity’ (D17=171 cases), followed by the group of ‘condensation humidity’ (82 cases) and the group of ‘wind entry’ (D5=75 cases). As for uncoated facades (U4), there were 14 ‘groups of pathology combinations’ and 55 types of pathology combinations. In this construction unit, the most numerous group was that due to ‘infiltration humidity’ (D17=73 cases), followed by the group of ‘condensation humidity’ (D15=60 cases) and the group of ‘capillary humidity’ (D16=31 cases). Finally, as for coated facades (U5), there were 15 ‘groups of pathology combinations’ and 86 different types of pathology combinations. In this construction unit, the most numerous group was that due to ‘infiltration humidity’ (D17=169 cases) followed by the group of ‘condensation humidity’ (D15=123 cases).

To be seen more easily, 3 different pathology combinations were chosen from the 44 groups of pathology combinations described in the two previous tables. These 3 pathology combinations had a larger number of cases by each construction unit (and therefore, the most important pathology combinations: 15 in total). These 15 pathology combinations were called ‘recurrent’ (see Table 4 and the terminology section at the end of the paper), and each was designated with a letter from A to O, as Figure 6 shows.

The recurrent combinations that obtained a larger number of cases as a whole (and called ‘frequent’ –marked with # in the table–) were as follows: ‘A’ *(‘Window frameworks’ - ‘Infiltration humidity’ - ‘Absence or deficiency of sealing’;146 cases; 7.19%* –see Figure 7–*)* and ‘G’ *(‘Flat roofs’ - ‘Direct infiltrations of water and/or dripping’ - ‘Deficient disposition of waterproofing sheet’; 93 cases; 4.58%)*.

Table 4 – The most recurrent pathology combinations per construction unit. A graphic is included in the middle that represents these pathology combinations in comparison with the total of cases.

CONSTRUCTION UNIT		DAMAGE	ORIGINAL CAUSE	CASES	REF
Window frameworks	U1	D17	C4*	146 #	A*
	U1	D15	C23	69	B
	U1	D17	C4	49	C
Pitched roofs	U2	D6	C9*	45	D*
	U2	D6	C5	28	E
	U2	D17	C9	25	F
Flat roofs	U3	D6	C8*	93 #	G*
	U3	D17	C8	78	H
	U3	D6	C21	71	I
Uncoated facades	U4	D15	C11*	37	J*
	U4	D17	C3	26	K
	U4	D16	C7	23	L
Coated facades	U5	D15	C23*	71	M*
	U5	D17	C3	59	N
	U5	D15	C11	49	O
In the right column ('Ref' –reference–), the dominant pathology combinations in each construction unit is marked with an asterisk (*). In the column of cases, the most frequent pathology combinations of the total studied in the research are marked with a hash (#).					

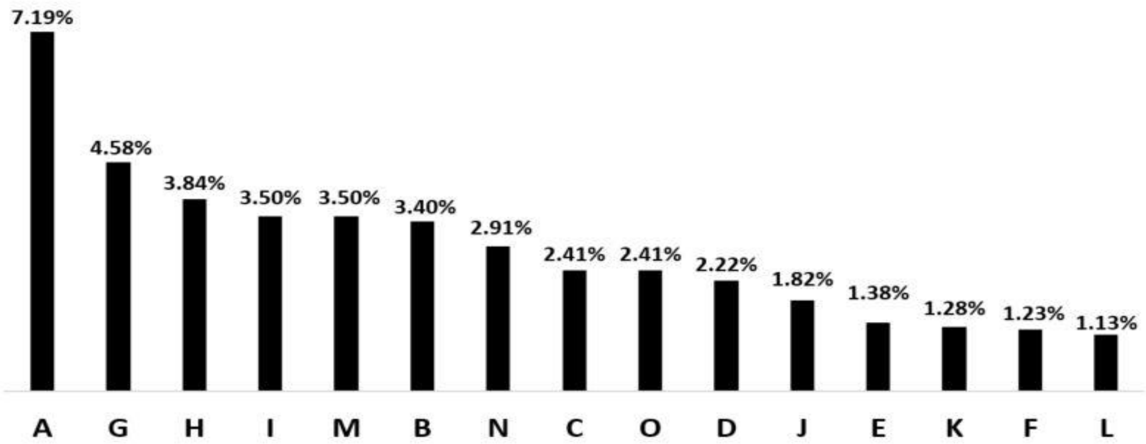

Figure 6 - Graphic with the most recurrent pathology combinations

A photographic example of the pathology combination A, which obtained the larger number of cases in this research on deficiencies in the external envelope (146 times). It is the damage due to infiltration humidity (D17), located in the construction unit of window frameworks (U1) and caused by the absence or deficiency of sealing (C4).

Photograph: Manuel J. Carretero-Ayuso

Figure 7 – Photography of a case that belongs to the pathology combination A

The following appraisals can be made from this table: damage D17 occurred 6 times, and damages D6 and D15 occurred 4 times. On the other hand, the original causes C3, C4, C8, C9, C11, and C23 occurred 2 times.

The most important interrelation U/D/C by each construction unit should be known, so they could be treated (either in project or in work) to reduce the number of deficiencies in future buildings. These interrelations were called 'dominant pathology combinations' (see the terminology section at the end of the paper) and are marked with * in Table 4. They corresponded to:

-Pathology combination A: There were 146 cases. They corresponded to '*window frameworks where there are damages of infiltration humidity caused by the absence or deficiency of sealing'* (U1/D17/C4).

-Pathology combination D: There were 45 cases. They corresponded to *'pitched roofs in which there are damages of direct infiltrations of water and/or dripping caused by the deficient disposition of tiles'* (U2/D6/C9).

-Pathology combination G: There were 93 cases. They corresponded to *'flat roofs in which there are damages of direct infiltrations of water and/or dripping caused by the deficient disposition of waterproofing sheet'* (U3/D6/C8).

-Pathology combination J: There were 37 cases. They corresponded to '*uncoated facades where there are damages of condensation humidity caused by an incorrect disposition of the thermal insulation'* (U4/D15/C11).

-Pathology combination M: There were 71 cases. They corresponded to '*coated facades where there are damages of condensation humidity caused by the existence of thermal bridges'* (U5/D15/C23).

3.4. Results per building typology

A comparative study of the percentages of each type of damage according to the building typologies (building block, isolated single-family, semi-detached single-family, and non-residential buildings) was conducted; this breakdown can be useful to understand where each building typology is more widespread. According to the values obtained in Table 5, the largest number of cases were in the building block as more than the half of the situations in the study occurred there (54.93%), and the most concentration damages were in D17 (18.62%) and D6 *(*10.10%). Based on the results obtained in the other typologies, humidity and infiltration were the most prevalent damages, regardless of the building typology considered.

Table 5 – Percentage of cases per type of damage and building typology

Code of the type of damage	Percentage of cases [%]				
	Block building	Isolated single-family	Semi-detached single-family	Non-residential buildings	Total
D1	0.10 *(100)*	0 *(0)*	0 *(0)*	0 *(0)*	0.10 *(100)*
D2	1.58 *(60.38)*	0.54 *(20.75)*	0.44 *(16.98)*	0.05 *(1.89)*	2.61 *(100)*
D3	0.25 *(33.33)*	0.44 *(60.00)*	0.05 *(6.67)*	0 *(0)*	0.74 *(100)*
D4	0.64 *(50.00)*	0.34 *(26.92)*	0.25 *(19.23)*	0.05 *(3.85)*	1.28 *(100)*
D5	2.17 *(58.67)*	0.59 *(16.00)*	0.89 *(24.00)*	0.05 *(1.33)*	3.70 *(100)*
D6	10.10 *(57.58)*	3.74 *(21.35)*	3.30 *(18.82)*	0.39 *(2.25)*	17.53 *(100)*
D7	2.07 *(58.33)*	0.49 *(13.89)*	0.99 *(27.78)*	0 *(0)*	3.55 *(100)*

D8	0.39 *(53.33)*	0.25 *(33.33)*	0.10 *(13.34)*	0 *(0)*	0.74 *(100)*
D9	2.46 *(78.13)*	0.25 *(7.81)*	0.39 *(12.50)*	0.05 *(1.56)*	3.15 *(100)*
D10	0.39 *(26.67)*	0.74 *(50.00)*	0.34 *(23.33)*	0 *(0)*	1.47 *(100)*
D11	0.34 *(58.33)*	0.20 *(33.33)*	0.05 *(8.34)*	0 *(0)*	0.59 *(100)*
D12	2.27 *(68.66)*	0.59 *(17.91)*	0.44 *(13.43)*	0 *(0)*	3.30 *(100)*
D13	0.79 *(66.67)*	0.25 *(20.83)*	0.15 *(12.50)*	0 *(0)*	1.19 *(100)*
D14	2.07 *(63.64)*	0.39 *(12.12)*	0.74 *(22.72)*	0.05 *(1.52)*	3.25 *(100)*
D15	7.34 *(47.00)*	3.94 *(25.24)*	4.09 *(26.18)*	0.25 *(1.58)*	15.62 *(100)*
D16	1.82 *(42.05)*	1.48 *(34.09)*	0.99 *(22.72)*	0.05 *(1.14)*	4.34 *(100)*
D17	18.62 *(55.83)*	5.91 *(17.73)*	7.78 *(23.34)*	1.03 *(3.10)*	33.34 *(100)*
D18	0.15 *(25.00)*	0.39 *(66.67)*	0.05 *(8.33)*	0 *(0)*	0.59 *(100)*
D19	0 *(0)*	0.05 *(25.00)*	0.05 *(25.00)*	0.10 *(50.00)*	0.20 *(100)*
D20	1.38 *(50.91)*	0.74 *(27.27)*	0.59 *(21.82)*	0 *(0)*	2.71 *(100)*
Sum	54.93 *(100)*	21.33 *(100)*	21.67 *(100)*	2.07 *(100)*	100 ---

Note: All values are expressed in percentages according to the existing cases.
The upper value is considered with respect to the total studied -2,030 cases-, and the value in brackets is considered with respect to the partial calculation of cases per type of damage.

4. DISCUSSION

4.1. Comparative analysis of the results with other studies

There is no international study that uses a methodology whose sources of information are the complaints of the building users/owners, that is specified by expert's reports issued by qualified technicians or that analyses 100% of existing cases in a nation in the period studied. This dataset could therefore be understood as an x-ray that reflects the pathology state of current building envelopes in Spain.

This research study is also important as other research studies have analysed the effectiveness and opportunity of interviewing users/owners in relation to the presence of construction deficiencies in their dwellings, thus concluding that this is not a reliable method to compile data (Milion et al. 2017). Therefore, the origin and way of obtaining data in this study -as indicated in the methodology- is a realistic and optimal alternative to know the most important damages of these construction units.

This marked singularity of the study implies a significant difficulty to present the results in other research studies and their contrast with different countries because studies with similar characteristics and starting data are required for a useful comparison. In addition, there is a relative deficit of publications about the faults and problems in buildings in comparison with other knowledge areas. As some authors detail (Lee et al. 2016), only the worst cases are known, and most are not published to protect the image or self-esteem.

However, some publications on construction damages could be considered, such as (Ilozor et al. 2004), in which some important statistics of United Kingdom are included. Although its goals and methodology are different from those of this paper, there is a great influence of damages related to water inside dwellings. Particularly, the typologies related to water penetration, condensation, retained water and humidities correspond to 50% of the total described in this paper. In parallel, Figure 2 presents the types of damages analysed, together with their frequency; although it is a different classification, the damages related to the presence of non-desirable water inside is also very significant. Thus, codes D17, D6 and D15 ('infiltration humidity', 'direct infiltrations of water and/or dripping' and 'condensation humidity') are all the damages called 'primary', whose impact is 66.51% of the total of damages.

Another study on envelopes was conducted in Portugal (Rodrigues et al. 2013), which is different from this paper as it looks for representative indexes of the degradation of envelopes in social dwellings and is based on surveys; however, fault data are introduced, thus containing common points. An indicator is applied to the buildings analysed in Portugal, the Performance Level (PL), which is used to measure satisfaction levels in relation to use requirements. Although there is no a direct concordance among the descriptors presented in this paper, in the final analysis of these indicators the Portuguese study gives importance to all the aspects related to water filtrations by quoting 'eliminate the causes of the envelope waterproofing faults' as the first priority for those responsible for the building maintenance. Thus, there is a relationship with this paper because the damages related to the non-desirable presence of water inside dwellings have been identified as 'primary damages'.

Other research studies address some of the units of envelopes, with roofs being the most specified issue. An analysis also conducted in Portugal could be stressed (Conceição et al. 2017, Conceição et al. 2019) in which there is certain parallelism in the assessment of causes. Although percentages cannot be compared (as each study refers to a different total of elements and the Portuguese study has a more segmented classification that makes difficult the accurate correspondence between them), there are certain similarities. Thus, the original causes of this paper corresponding to C8 (deficient disposition of waterproofing sheet), C21 (deficient junction with roof bowls and drains) and C28 (inappropriate slope of the roof element), are reflected in the Portuguese research with the codes A-G7 (absence/inadequate layer positioning), A-S8 (defects in the tail ends) and A-G9 (inadequate slope/ponding), whose frequency is also high.

Finally, although there is no an international contrast as it is also located in Spain, a research was conducted in the university buildings at the Polytechnic University of Catalonia (Bortolini and Forcada 2018). Its methodology is based on surveys and teaching buildings, but the final conceptual results are similar to those of this paper. In both situations, the problems related to water input or humidities in the envelope correspond to percentages greater than 65% of the total.

4.2. General considerations

Generally, the specific development of pathology combinations (qualitative and quantitative interrelation between U/D/C) is not included in research studies, nor, based on these combinations, the possibility of presenting the general construction epidemiology of a country. The great difficulty of obtaining large datasets of damages not occurring in a concrete building/zone or in a building typology of which a specific aspect is to be studied is the main reason why the pathology combinations are not studied at a large scale. Providing its frequency and characterization from empirical and actual data is particularly something of a challenge. As this study used many data, the existing pathology combinations were deeply studied and analysed in the 5 construction units: these construction units corresponded to both the total of data in the studied period and the total of territorial data in Spain (i.e. this paper does not present a statistical sample but the total calculation of the lawsuits filed in courts in all country).

Thus, it is worth stressing that this study is only based on the existing damages in the building envelopes of complaints filed in courts. By definition, other less important problems without having filed a demand cannot be studied because they would not be included in the information source used (sentences of the Spanish Administration Justice), thus implying that data would not have the required uniformity and approach. Other damages not included in this research could be solved through voluntary arbitration; however, they would be few as this procedure is rare in Spain.

All the information here presented could be of great interest to the technicians involved in the construction process (either in the project phase or in the execution phase), and their knowledge could be significantly helpful to pay attention to the most conflictive and pathology points, thus avoiding repeated errors, optimizing the operation of buildings, and contributing to their sustainability (Adabre et al. 2020).

4.3. Particular considerations

Considering the types of the original causes indicated in Table 1 can be useful to check how the singular points of facades, windows and roofs are treated (in both the project and execution), and generally, if the basic criteria of a good construction are considered (Carretero-Ayuso 2017, Carretero-Ayuso 2018).

It is significant that, among the 20 types of damages, the four types of damages with more cases are those related to the presence of water (D6, D15, D16 and D17). This is a very important aspect to be considered, and the Basic Document on Healthiness of the Spanish Building Technical Code (CTE/DB-HS-1) (Ministerio de la Vivienda 2006) becomes important as it includes the design and execution conditions that should be respected in buildings in relation to the degree of impermeability, watertightness conditions, etc.

The 5 dominant pathology combinations were also related to the presence of water, in accordance with what has been verified in other references. Therefore, there is an emphasis on their original causes related to heterogeneities or construction critical points of the envelope. According to all the information previously included in the Results section, the interrelations U1/D17/C4 (also identified as ‘A’) and U3/D6/C8 (also identified as ‘G’) were simultaneously recurrent, frequent, and dominant pathology combinations.

5. CONCLUSIONS

Five construction units that belong to the external building envelope are studied, thus determining the damages and their original causes. The construction units with more cases are coated facades (U5= 29.75%) and flat roofs (U3=27.09%). The most frequent types of damages are ‘infiltration humidity’ (D17=33.35%), ‘direct infiltrations of water and/or dripping (D6=17.54%) and ‘condensation humidity’ (D15=15.62%); moreover, D15 and D17 are the damages which occur in the 5 construction units. The original causes with a greater percentage presence are the ‘absence or deficiency of sealing’ (C4=14.38%), ‘deficient disposition of waterproofing sheet’ (C8=9.01%), and the ‘existence of thermal bridges’ (C23=7.98%).

Based on the analysis, 228 different types of pathology combinations are characterized (interrelation construction unit/damage/original cause). The most prevalent pathology combinations in each construction unit are due to the problems related to the presence of water (damages D6, D15, D16 or D17 are present). The most important interrelations are U1/D17/C4 (*window frameworks where damages of infiltration humidity caused by the absence or deficiency of sealing occurred)* and U3/D6/C8 *(flat roofs where damages due to direct infiltrations of water and/or dripping caused by the deficient disposition of waterproofing sheet occurred)*. If precautions could be taken when writing the project or performing the construction works to reduce the pathology combinations indicated, the damages and the number of demands would be mostly reduced.

Furthermore, the relative frequency of the 20 types of damages has been broken down and quantified according to the building typology in which they occurred, and the result is that 54.93% occurred in building blocks. Among them, the greatest concentrations are obtained in ‘infiltration humidity’ (D17=18.62%).

The methodology and the results of this investigation could be of interest for researchers from other countries who want to know the existing damages in buildings based on the lawsuits filed by users/owners. With the information obtained, the various agents involved in the construction process could implement control systems to reduce the non-quality processes in the design and execution phase. Results could be improved by including enough constructive details in the projects, not omitting basic information of both the characteristics of the materials and the development processes in works and improving the feedback between designers and site managers.

A further study could be based on the assessment of envelope damages by using neural networks.

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7. TERMINOLOGY

- GENERAL DESIGNATIONS

  Case: Each interrelation among a construction unit, a damage and an original cause, considering the number of times they take place. There are 2030 cases.

  Construction unit: Each element which is part of the envelope of a building.

- DESIGNATIONS OF DAMAGES

  Primary damages: The damages whose individual weight within the general calculation is greater than 15%. There are 3, and their sum is 66.51% of the total. Among them, that obtaining the essential weight of the occasions (that obtaining the greatest value) is called 'critical primary damage', and the remaining are called 'basic primary damages'.

  Secondary damages: The damages whose individual weight within the general calculation is greater than 2% and lower than 15%. There are 8, and their sum is 26.59% of the total.

  Trivial damages: The damages whose individual weight within the general calculation is lower than 2%. There are 9, and their sum is 6.90% of the total.

- DESIGNATIONS OF THE ORIGINAL CAUSES

  Hyper-common original cause: The original cause which is in the first place. Its presence is greater than 10%, and there is only 1 among the 33.

  Usual original causes: Their presence is between 5% and 10%. There are 4 original causes.

  Occasional original causes: Their presence is between 2% and 5%. There are 11 original causes involved in this bracket.

  Residual original causes: Their presence is lower than 2%. There are 17 original causes meeting this condition.

- DESIGNATIONS OF PATHOLOGY COMBINATIONS

  Pathology combination: It is the typology and construction interrelation between the three descriptors (construction unit, damage, and original cause), so the type of damage in a certain type of construction unit and caused by a type of specific original cause is exemplified.

  Different pathology combinations: Expression to emphasize the pathology combinations from the point of view of their diversity (different types of pathology combinations) and quantity (there are 228). In other words, from the 2030 cases, there are conceptually 228 different interrelations repeated, as Tables 3 and 4 indicate.

  Recurrent pathology combinations: Each of the first 3 pathology combinations with a larger number of cases with respect to a construction unit. There are 15 in total.

Dominant pathology combinations: This is the most important pathology combination per number of cases within a construction unit. There are 5. They obtain a greater value among the recurrent pathology combinations.

Frequent pathology combinations: The pathology combinations that globally obtain most cases (regardless of the construction unit in which they take place). There are 2.

Groups of pathology combinations: The pathology combinations that share the same type of damage within a construction unit, only differing in the original cause causing them. There are 44 (34 in the vertical envelope and 10 in the horizontal envelope).

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