EXTERIOR BRICK WALLS: LEARNING NON-QUALITY THROUGH FAILURES AND CLIMATE-PATHOLOGICAL DISTRIBUTION

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ABSTRACT

The object of this research is to identify the list of climatological variables involved in the appearance of construction failures in the external walls of dwellings, through the analysis of over one thousand cases. The data source used consisted of the judicial records of the Justice Administration, a source to which few researchers have access, given the dispersion of the data and the permissions required to access it. Once obtained, all situations pertaining to dwellings were read and annotated, until 100% of the cases were accounted for, and percentages of recurrence were calculated for each of the 9 different types of failures that were described. A study was carried out by 'strips of climatic location' according to four climatological variables (situation, latitude, climate and annual rainfall) that were sorted from largest to smallest to obtain the 'ranks of pathology concentration' according to the resulting preponderance. With these results, technicians will be able to know the most problematic climate-geographical areas, through the determination of the ranks of normalised frequencies, allowing them to take the necessary measures during the construction process. The lessons learnt can be incorporated in maintenance plans to optimise preventive maintenance frequency and actions.

KEY WORDS

Failures, facades, buildings, climatology, environmental conditions

1.- INTRODUCTION

1.1.- General vision and lines of research

External walls are the vertical part that envelops the structure of the building and, along with the roof, they constitute the first protection barrier against external agents (Monjo Carrió and Lacambra Montero 2007). These external walls also play an important role in the energy balance of buildings (Srisamranrungruang and Hiyama 2021). Depending on its design and construction, a building may possess an effective thermal envelope or it may have any number of discontinuities in its insulating membrane, leading to the appearance of thermal bridges (de Freitas et al. 2014).

Given the diversity of available construction systems (Gaspar et al. 2016) and the significant number of components in envelopes (Carraro and Oliveira 2015), external walls are one of the most problematic parts of buildings (Ilozor et al. 2004). This results not only from the way they're built but also from the way they are conceived in the design phase (Carretero-Ayuso and García-Sanz-Calcedo 2018). Regarding this latter phase, the aim of finding a solution that is perfect from a perspective of execution (Hradil et al. 2014) makes it especially difficult to produce an optimal design (Molnár and Ivanov 2016a).

There is, in the international literature that was reviewed, a line of research that goes more deeply into a number of construction problems and deficiencies with various specific points of focus: the study of ceramic cladding through artificial neural networks (Souza et al. 2020), degradation as a result of humidity (Pereira et al. 2018), problems associated to interventions in building rehabilitation (Díaz 2006), behaviour of different finishing treatments (Bauer et al. 2015), verification of water penetration in external walls (Duarte et al. 2011), economic cost of defects (Mills et al. 2009), volume of air infiltrated through the envelope (Van Den Bossche and Janssens 2016), etc. These studies are all complementary to the traditional line of research on constituent materials of the envelope, such as bricks (Molnár and Ivanov 2016b) and cement mortars (Ramírez et al. 2019), and on the creation of new nano-improved products (Martin et al. 2019).

Some other research examines interesting aspects in relation to durability requirements against external agents (Pakkala et al. 2014), through different methodologies. Some papers analyse the conditions of buildings' environment (Hamdy et al. 2017) and the durability of the materials used in their construction (Richardson 2002). Several of these studies point to interrelations with research on life cycle and prediction of building service life (Grant et al. 2014), which evolve differently based on the construction systems used (Gaspar and De Brito 2008) (Ximenes et al. 2015) (Galbusera et al. 2015).

1.2.- Design phase

For some researchers (among those consulted and previously referenced in this section), the number of failures in construction can be lowered by producing designs that are well structured and detailed, and in which an a priori analysis is carried out to determine which problems the specific design might entail (Chong and Low 2006). It is common to establish quite specific criteria for how the works should be carried out and to establish verification systems for how workers should carry out their activities, so that the expected construction quality can be met. Nevertheless, this perspective, of outlining procedures and control points, is not widespread among designers nor among those involved in construction activities (Garcez et al. 2012). In order to test this aspect, two researchers in Spain (Carretero-Ayuso and García-Sanz-Calcedo 2018) analysed the design failures common in the envelope of health care buildings, through a homogeneous sample of different projects. They detected 344 incidents, materialised in 51 control parameters, observing that a large part of the detected failures was related to 'omission of data' (39%) and to 'lack of definition of the technical prescriptions' (25%).

For some authors (Azorín López and Monjo Carrió 2005) it is imperative to carry out a study of the eventual failures and damages that designs can lead to, due to these failures and damages' economic impact. To illustrate this point, below are indicated three unusual cases related to the envelope of famous buildings.

In order to reduce repair costs, the occurrence of unforeseen situations, and the need for corrections and renovations, as well as to improve simplicity and effectiveness in drafting the projects, many authors consider it necessary for developers and builders to start considering and measuring those costs to be able to understand their true magnitude and determine their real causes (Love 2002). On the other hand, the existence of an adequate quality management system for the design phase ensures greater comfort (both for users and for building owners), as well as greater assurance that the building's effectiveness will last throughout the expected service life (Alba Cruz et al. 2013).

1.3.- Execution phase and the period of maintenance

A study of the University of Switzerland (Pahud et al. 2005) found that the fact that certain buildings were built in a single construction surge resulted into a significant increase of maintenance works in a short amount of time. Nevertheless, smaller failures do not always receive the same attention and are not repaired, leading to customer dissatisfaction and harmful effects for the builder's reputation (Forcada et al. 2013). Other authors (Azhar 2011) found a positive correlation between the number of last minute changes during the execution phase and the number of failures.

In order to reduce the need for last minute changes to the characteristics of the materials or construction systems being used, other researchers (Pauwels 2014) considered that when building information modelling (BIM) technology is totally incorporated in the construction, the probability of failures appearing in a building is drastically reduced (The American Institute of Architects 2013). In Spain, BIM technology (Ministerio de Fomento 2015) still has a low adoption rate, and in the execution phase there is currently insufficient technological and social maturity to be able to realise this reduction in construction failures (and in the improvement of production times and cost reduction (Chou et al. 2009)). Nevertheless, this does not prevent carrying out a proactive reading of the failures occurring today and learning about the costs of re-work as opportunities for self-instruction (Love et al. 2018) and improving the construction sector (Mills et al. 2009).

On the other hand, some of the failures in construction originate from inadequate or non-existent maintenance – a quite generalised problem in the Spanish building stock (Mesa Fernandez et al. 2016). As such, updates and maintenance gain increasing importance (Arencibia 2007). However, not all maintenance actions fulfil their function well, which is why some research has also assessed the degradation of external walls (Galvão et al. 2020) and exterior carpentry resulting from inadequate conservation and renovation actions (Rodrigues et al. 2019). Another problem is that of implementing an adequate maintenance plan in complex units such as facades and their cladding (Ferreira et al. 2021). This is the reason for which a number of Portuguese researchers have proposed a methodology with multiple criteria to prioritise the actions to be taken (Madureira et al. 2017), given that, among other reasons, it is quite different if parts of the envelope are finished with ceramic cladding (Souza et al. 2018), with continuous mortar finishing (Galvão et al. 2018), or others. In order to facilitate these decisions, as well as to sequence building inspection processes, it would be quite useful to use specialised software (Silva and de Brito 2019).

1.4.- Research focus

No existing research papers were found (by other authors or from other countries) that included as their data source the expert reports of the judicial complaints filed by property owners, or that focused on how the failures existing in buildings' external walls are influenced by the climatic conditions of the locations in which they are found.

The objective of this research, then, is to determine which types of failures occur more commonly in the external walls of dwellings and what is their distribution according to the Spanish climatic areas (all of which is done based on court sentences). The structure of the article, then, is based on establishing a general methodology (data source, identification of climates and characterisation of the cases analysed) and on specifying the results found in the research as follows: results by finishing variant and affinity group, result by type of construction failure, result by building typology, and climate-geographical study.

2.- METHODOLOGY

2.1.- Data source

This paper presents the data collection, classification, analysis, and results obtained in a specific construction element: the external walls of dwellings made with bricks. To this effect the methodological grounding of the regulation UNE 41805-1 (AENOR 2009) on actions for the investigation, identification, and evaluation of failures was considered.

The documental basis consists of the data extracted from the records of the civil responsibility insurance of Spain’s building surveyors and technical architects (MUSAAT 2018). All records meet the condition of being related to a judicial complaint filed between the years 2016 and 2018 and having reached final – unappealable – sentencing, issued during the following years (SERJUTECA 2016-2018). For this reason, it was necessary to wait for the conclusion of a long legal and administrative process to be able to start to introduce the cases in this research and, lastly, handle all their data. This process implies going through levels of courts (with the corresponding waiting times between each level) to arrive at the point when cases are no longer appealable to higher courts. Moreover, data entry was not finalised until 100% of the cases existing in Spain were included. In other words, the data set consists of the total set of the country, and not just of a partial sample.

All of the above starts when the owner of a property faces construction problems and the builder does not solve them, which forces the owner to resort to the courts of law. At that point, owners also file complaints against technicians that have participated in the construction process (both the author of the project and the construction manager). The reason for which complaints are filed against technicians is that, in Spain, these technicians must by law be covered by civil responsibility insurance – unlike construction companies and developers, which are not obliged to have this insurance.

The collection and analysis of the data is described in Table 1.

[TABLE 1 HERE]

In this research, a total of 1043 cases of construction failures were found to have a connection with the external brick walls of dwellings (398 in 2016, 349 in 2017, and 296 in 2018). There are two finishing variants in these external walls: cladded walls – with rendering – (W1) and facing walls –brick-faced walls – (W2). The data collection was systematised accordingly, yielding a characterisation of 9 types of construction failures (TCF) that are indicated in Figure 1 and are defined at the end of the paper.

[FIGURE 1 HERE]

In the international literature reviewed for this paper (Love and Smith 2003) (Carretero-Ayuso et al. 2016) (Mydin 2015), it was found that many publications on construction failures focus on buildings belonging to the same developer or that were built by the same construction company. In other cases (Krishnamurthy 2007) (Raposo et al. 2011), studies are based on surveys or limited percentages of the data source used. In this research, however, there is no variable that can connect the cases between them, as they are judicial cases that are independent one from another. This allows to ensure that the obtained results do not have any type of bias and that the lessons learnt are independent and more general.

Additionally, this research makes quite a unique contribution to the scientific knowledge of civil engineering: the totality of the cases contained in the data source, and for all of the years in the period in question, is included and studied. As a result, there is a low probability of error, given that the data set consists of the full population (100% of the cases).

2.2.- Identification of climates

A novel analysis is carried out regarding climatological conditions (IDAE 2010). It was decided to analyse the variability of the number of cases of construction failures according to four climate-geographical variables (Belda et al. 2014; Useros Fernández 2013), given the impression that the number of failures would be affected by the climate location.

It is intended, as such, to analyse the predominance that these external factors can have on external walls, taking into account the percentage difference according to them. In this way, knowing the location in which each of the construction failures took place (according to their location in the administrative divisions of Spain), they were assigned to the variables shown in Table 2. The values were collected from the data provided by the Spanish State Meteorology Agency (AEMET 2020).

[TABLE 2 HERE]

The normal temperatures for these climates, within Spain, are indicated below. The Köppen-Geiger classification is indicated in parentheses. The oceanic climate [Cfb] has an annual weighted mean temperature of 13.6°C (56.5ºF) *(during the winter the mean temperature reaches 8.5°C (47.3ºF) and in summer it reaches 19.2°C (66.6ºF)).* The continental climate [Csb] has an annual weighted mean temperature of 14.3°C (57.7ºF) *(during the winter the mean temperature reaches 7.4°C (45.3ºF) and in summer it reaches 23.2°C (73.8ºF)).* The Mediterranean climate [Csa] has a annual weighted mean temperature of 18.1°C (64.6ºF) *(during the winter the mean temperature reaches 11.8°C (53.2ºF) and in summer it reaches 26.7°C (80.1ºF)).* The subtropical climate [Cwa] has an annual weighted mean temperature of 22.3°C (72.1ºF) *(during the winter the mean temperature reaches 18.1°C (64.6ºF) and in summer it reaches 25.4°C (77.7ºF)).*

Using these variables, a global percentage study of construction failures will be carried out to obtain the ‘percentage of presence of cases’ (%PC) that will, in turn, enable the determination of the ‘strips of climatic location’. This is done by applying each variable one by one, and later combining them in pairs and also three at the time. Subsequently, they are combined in fours, allowing to obtain the 'percentage of construction failures' (%CF). This value %CF will be used to create the 'ranks of pathology concentration' that are the grouping of different areas of climatic location.

Lastly, all percentages are grouped in descending order to establish the climate-geographical areas (AREA 1, AREA 2, AREA 3 and AREA 4), that quantify and classify the entirety of the Spanish territory according to these conditions.

2.3.- Characterisation of the cases analysed

As for the construction characteristics of the studied element (exterior walls), it can be stated that, in general, construction systems in buildings in Spain are usually quite homogenous. As a result, nearly all exterior walls in housing buildings are done with brick.

The cases analysed herein correspond to walls of a thickness between 11 cm *(4.3 in.)* and 11.5 cm *(4.5 in.)*, done with perforated clay engineering bricks (it is a very compact brick with several circular holes, all arranged vertically) and between 23.5 cm *(9.3 in.)* and 24 cm *(9.5 in.)* longitudinally and 7 cm *(2.8 in.)* or 9 cm *(3.5 in.)* in height. Cement mortar is placed between the bricks, and the thickness of these joints is of between 0.8 cm *(0.3 in.)* and 1.2 cm *(0.5 in.)*.

All the analyzed walls are part of the envelope (they are not load-bearing walls since the structural elements are the slabs and the pillars). The types of cement mortar that were used are the general masonry ones, M-5 or M-7.5 N/mm^2 *(N/0,00155in^2.)*. The walls are double brick walls, with insulation in the air chamber, according to the Spanish standard. The external brick, may or not be, clad externally, and the interior brick, in many cases, is hollow brick.

When the walls are cladded (W1), the facade is then covered with a render of cement mortar and river sand, with an average thickness of 2 cm *(0.8 in.)*. When they are facing walls (W2), i.e., not cladded, it means that the bricks used have been fabricated to allow using them in this way, since the surface of the exposed side (which faces the outside) has a better and more aesthetic finishing.

For each of the cases analysed, in addition to determining the finishing variant (W1=717 cases, or W2=326 cases), the building typology was also noted: apartment blocks (661 cases) or houses (382 cases).

In addition, a full and detailed breakdown of the number of cases was carried out, according to each of the climate-geographical variables. The reader can thus see the segmentation according to these concepts. Table 3 shows all of this, also including the subtotals and totals for a better understanding of the set.

[TABLE 3 HERE]

3.- RESULTS

3.1.- Result by finishing variant and affinity group

The distribution of cases according to finishing variant is quite diverse, as shown to the left of Figure 2. Cladded walls concentrate over two thirds of the total (W1=68.74%; 717 cases), while facing walls do not reach one third of cases (W2=32.16%).

It was intended to compare failures according to the similarity of their own nature. To this end, affinity groups were constituted as shown below:

- Group of failures by humidities (TCF1+TCF2+TCF3) = HFG

- Group of failures by cracking (TCF4+TCF5+TCF6) = CFG

- Group of various failures (TCF7+TCF8+TCF9) = VFG

As can be noted to the right of Figure 2, the affinity group with the highest recurrence is HFG with 58% of the total (603 cases), followed by CFG with 36% (379 cases).

[FIGURE 2 HERE]

3.2.- Result by type of construction failure

Figure 3 shows the number of cases found for each of the 9 types of construction failures. The type of failure with the most cases was ‘humidity by infiltration’ (TCF1=287), which represents 27% of the total. It is followed by ‘humidity by condensation’ (TCF2=215) and ‘fractures and detachment of pieces’ (TCF4=150).

[FIGURE 3 HERE]

3.3.- Result by dwelling typology

The cases were broken down according to the dwelling typology in which they occurred (see Figure 4). Most of the time (nearly two thirds of the time), failures were concentrated in apartment blocks (689 cases). Just over a third occurred in houses, be they detached or attached to other houses. It should be noted that these general values are in accordance with the dwelling typology built in Spain, where there is a clear preponderance of apartment blocks.

[FIGURE 4 HERE]

3.4.- Climate-geographical study

3.4.1.1.- Distribution of failures according to climate variables

The variables ‘situation, ‘latitude’, ‘climate’ and ‘annual rainfall’, indicated in Table 2, the dwelling typology, and the finishing variants W1 and W2 are interrelated to the construction failures shown in Figure 3 in different ways and intensities. The percentage of recurrence is expressed in the following sections, sorted by type of construction failure.

- Humidity by infiltration (TCF1)

It was observed that this construction failure is clearly less frequent in facing walls (W2=28.92%) than in cladded walls (W1=71.08%). It occurs more often in the mediterranean (36.59%), oceanic (31.71%) and continental (27.87%) climates than in the subtropical climate (3.83%). It was also found that this failure is more frequent in the north latitude (67.25%) than in the central (20.21%) or south (12.54%) latitudes. It occurs more often in coastal areas (67.25%) than in zones located in the interior (32.75%), and more often in zones with intermediate rainfall (55.05%) ~~that~~ than in high (30.32%) or low (14.63%) rainfall. Lastly, the distribution by dwelling typology was of 69.34% in apartment blocks and 30.66% in houses.

■ Humidity by condensation (TCF2)

This failure has a much smaller percentage in facing walls (W2=30.70%) than in cladded walls (W1=69.30%). It was shown that the highest presence is in the mediterranean (38.14%) and oceanic (34.42%) climates, followed by the continental (25.58%) climate – in the subtropical climate it is residual (1.86%). It occurs more commonly in the north latitude (67.44%), than in the central (20.47%) or south (12.09%) latitudes, even though it also appears less frequently in the interior (26.98%) than in coastal areas (73.02%). It was also shown that this failure has a higher frequency in areas with intermediate rainfall (50.70%), than in areas with low (34.42%) or high (14.88%) rainfall. In turn, the distribution according to dwelling typology was of 52.09% of cases in apartment blocks and 47.91% in houses.

■ Humidity by capillarity (TCF3)

The finishing variant in which this failure occurs the most is cladded walls (W1=64.36%), as opposed to facing walls (W2=35.64%). It is quite frequent in the mediterranean climate (42.57%), has an average frequency in the continental (27.72%) and oceanic (23.76%) climates, and a low frequency in the subtropical climate (5.95%). It occurs more frequently in the north latitude (58.42%), than in the central (21.78%) or south (19.80%) latitudes, and has a higher degree of presence in coastal areas (66.34%) than in the interior (33.66%). It was also shown that it occurs strongly in zones with intermediate rainfall (60.40%), moderately in zones with high rainfall (23.76%) and less in zones with low rainfall (15.84%). In turn, the distribution according to dwelling typology was of 50.50% in apartment blocks and 49.50% in houses.

■ Fractures and detachment of pieces (TCF4)

The TCF4 failure appears more often in cladded walls (W1=72.00%) than in facing walls (28.00%). As for the variable C (type of climate), it occurs with much more frequency in the mediterranean climate (47.33%) than in the continental (24.01%) and oceanic (25.33%) climates, and even less in the subtropical climate (3.33%). As for the variable B (latitude), it occurs almost in equal measure in the south (14.67%) than in the central part (15.33%), but it is extraordinarily frequent in the north latitude (70.00%). If we consider proximity to the sea, there is a greater percentage in coastal areas (72.67%) than in the interior (27.33%). In relation to rain, there is a higher value in areas of intermediate rainfall (56.00%), followed by high (24.67%) and low (19.33%) rainfall. In turn, the distribution according to dwelling typology was of 71.33% in apartment blocks and 28.67% in houses.

■ Fissures in the wall pane (TCF5)

In TCF5 almost two thirds of cases occur in cladded walls (W1=66.42%), and far less in facing walls (W2=33.58%). There is quite a high expression of this failure in the mediterranean climate (36.57%), quite similar percentage values between the continental (30.60%) and oceanic (29.85%) climates, and a very low presence in the subtropical climate (2.98%). It occurs more frequently in the north (68.65%), which is followed by the central latitude (20.90%) – it occurs infrequently in the south latitude (10.45%). It was also found that it is concentrated more in coastal areas (67.16%) than in the interior (32.84%). As for rainfall, it occurs more often in zones with intermediate intensity (56.72%), followed by high rainfall (28.36%) and much less often in low rainfall (14.92%). In turn, the distribution according to dwelling typology was of 67.16% in apartment blocks and 38.84% in houses.

■ Fissures in finishing elements (TCF6)

There is a clear preponderance of TCF6 in cladded walls (W1=70.53%) over facing walls (W2=29.47%). It occurs much less in the subtropical climate (7.37%) than in the oceanic (25.26%), continental (31.58%) and mediterranean (35.79%) climates. It has a low presence in the south latitude (15.79%), moderate in the central latitude (23.16%) and high in the north latitude (61.05%). It also occurs less often in the interior (33.68%) than in coastal areas (66.32%). Equally, it was found that this failure is more common in zones with intermediate rainfall (54.74%) and with similar percentages between zones of high rainfall (25.26%) and low rainfall (20.00%). In turn, the distribution according to dwelling typology was of 76.84% in apartment blocks and 23.16% in houses.

■ Appearance of efflorescences (TCF7)

This type of failure occurs more in cladded walls (W1=58.06%) than in facing walls (W2=41.94%). They are predominantly (about half of the cases) in the continental climate (45.16%), they occur rarely in the subtropical climate (6.45%) and with some frequency in the mediterranean (25.81%) and oceanic (22.58%) climates. As for latitude, it was found that this construction failure appears more than half the time in the north latitude (54.84%), quite infrequently in the south (12.90%), and the rest of the time in the central part (32.26%). It occurs slightly more often in the interior (51.61%) than in coastal areas (48.39%). Intermediate rainfall is present in almost 6 out of 10 cases (58.06%); 1 out of 10 cases occur in low rainfall (25.81%); and the remainder in high rainfall (16.13%). In turn, the distribution according to dwelling typology was of 61.29% in apartment blocks and 38.71% in houses.

■ Anomalies in the insulation (TCF8)

The finishing variant that has the most cases is facing walls (W2=55.56%), somewhat above cladded walls (W1=44.44%). By type of climate, the mediterranean covers about two thirds of the occurrences (61.11%); one third of occurrences are in the continental climate (33.33%); there is a very low frequency in the oceanic climate (5.56%); and it does not occur at all in the subtropical climate (0%). As for latitude, more than 6 out of 10 times occur in the north (61.11%); they practically do not occur at all in the south (5.56%); and the rest of the occasions take place in the central latitude (33.33%). As for their situation, two thirds are in coastal areas (66.67%) and one third part in the interior (33.33%). As for the variable D, there is a clear predominance of intermediate rainfall (72.22%), a moderate frequency for low rainfall (22.22%), and very rare for high rainfall (5.56%). In turn, the distribution according to dwelling typology was of 38.89% in apartment blocks and 61.11% in houses.

■ Imperfections in the planimetry (TCF9)

It was found that construction failure has a very low presence in facing walls (W2=25.00%) when compared to cladded walls (W1=75.00%). This failure also does not occur in the subtropical climate (0%); it has a low percentage in the oceanic climate (16.67%); precisely one third of cases occur in the continental climate (33.33%); and half of all cases are in the mediterranean climate (50.00%). The central latitude accumulates one third of the cases (33.33%), the south has a modest percentage (16.67%), and the other half of the cases is found in the north latitude (50.00%). As for the situation, frequency is lower in the interior (41.67%) than in coastal areas (58.33%). In turn, there is a completely dominant frequency in intermediate rainfall (75.00%), a moderately representative frequency in low rainfall (16.67%), and a frequency of little significance in high rainfall (8.33%). Lastly, the distribution according to dwelling typology was of 25% in apartment blocks and 75% in houses.

3.4.1.2.- Determination of strips of climatic location

Once the number of cases was found for each type of construction failure, it was decided to quantify and evaluate the percentage distribution of the global set of the 1043 cases according to the 3 first climate-geographical variables (situation, latitude and climate). One thus obtains the ‘percentage of presence of cases’ (%PC), that corresponds to the different cases (named ‘strips of climatic location’) that result from applying the classes in which the variables A, B, and C of Table 2 are sub-divided.

[TABLE 4 HERE]

The individual value obtained by each of these variables is expressed in the upper section of Table 4, it being shown that the north latitude and coastal areas are the most problematic locations (concentration of failures of 65.77% and 68.36%, respectively). Subsequently, variables A, B, and C were combined in pairs, and their values collected in the middle section of the same table. It can be observed that there are two strips of climatic location that garner results far greater than the remainder: ‘Coastal-North’ with 46.21% and ‘Coastal-Mediterranean’ with 37.97%.

The variables were also combined in threes (see lower section of Table 4) to determine the combined values, it being noted that the strips of climatic location in which the most cases occurred are ‘Coastal-North-Oceanic’ with 26.56% and ‘Coastal-North-Mediterranean’ with 19.65%.

3.4.1.3.- Specification of areas according to ranks by normalised frequencies

In this phase of the research, the results obtained in the lower part of Table 4 (combination of variables in threes) are characterised, transforming the 10 ‘strips of climatic location’ into 4 ranks of pathology concentration (which will be termed ‘climate-geographical areas’) that are described in Table 5. Thus, a quadrant is established in which each one of these climate-geographical areas is defined according to the percentage of presence of cases of the construction failures in the walls (%CF). If this value is greater than 18, it will belong to AREA 1, if %CF is between 10 and 18 it will belong to AREA 2, if %CF is between 5 and 10 it will be in AREA 3 and, lastly, if %CF is equal to or lower than 5 it will be in AREA 4. These values are set on how close the individual percentages are to each other and the determination of the closest whole number of them.

In order to enable easy perusal of the data, next to the name of each strip of climatic location is shown the individual value of its percentage, as well as the sum of the 'total %CF' that groups the area to which it belongs. A column (relative frequency) is also included, incorporating the relation of the percentage of construction failures obtained according to the number of dwellings existing in that part of Spain (INE 2020) (the calculations were carried out considering the value existing for each of the strips of climatic location). Given that the values of the relative frequencies obtained were not high, those values were normalised to obtain a 'standardised relative frequency', for which the value of the highest relative frequency (AREA 1) was assigned a value of 1, while the values remaining referred to this value. This normalisation is what allowed the creation of AREAS 1, 2, 3, and 4.

Analysing the distribution of the data in Table 5 it can be noted that AREA 1 corresponds clearly to all buildings located in the coastal part of the country that are situated in the north latitude. This area is the most critical, and the one which concentrates the most failures.

[TABLE 5 HERE]

[TABLE 6 HERE]

In the following phase of the research, the fourth variable (annual rainfall), was included in the analysis, to observe which results and variations would be found (AEMET 2020). Table 6 shows these results, incorporating the three classes in which annual rainfall is subdivided (High/Intermediate/Low). Behind this incorporation there are 4 geographical location strips in Table 5, divided in two parts (resulting in 8 in total). They are: 'Interior-North-Oceanic' (broken down into intermediate rainfall, with %PC=1.05%, and high rainfall, with %PC=1.35%), 'Coastal-South-Mediterranean' (broken down into intermediate rainfall, with %PC=2.01%, and low rainfall, with %PC=5.37%), 'Interior-Central-Continental' (broken down into intermediate rainfall, with %PC=7.67%, and low rainfall, with %PC=2.11%) and 'Interior-North-Continental' (broken down into intermediate rainfall, with %PC=11.98%, and low rainfall, with %PC=5.28%). These strips are identified in Table 6 with an asterisk (*) according to the breakdown described above.

Sorting the results again, in descending order, it can be seen that:

- AREA 1 remains unaltered in its configuration and percentage.
- AREA 2 keeps the 'Coastal-Central-Mediterranean' strip and the intermediate rainfall part of the 'Interior-North-Continental' strip.
- AREA 3 goes from being formed by two strips to being formed by strips.
- AREA 4 goes from being formed of four strips to being formed by seven strips.
- The set of the distribution of the climate-geographical areas remains with the same limit values of %CF, but with a final number of 14 strips, as shown in Table 6).

It can be indicated that the inclusion of annual rainfall (as a specific variable) does not bring with it a relevant measure of added value that changes the general distribution of failures in the climate-geographical areas (it is not a factor that substantially changes the order of the percentages of the results when characterising failures with the other 3 variables simultaneously).

4.- DISCUSSION

4.1.- General considerations

From the time buildings are handed over to developers, a specific maintenance calendar should be established. In Spain, current legislation (Jefatura del Estado 1999) indicates several of the actions that should be carried out (Ministerio de la Vivienda 2006). However, they are often not carried out, given the lack of social awareness of this aspect. Once the first period of use has passed, property owners decide to file lawsuits against the technicians participating in the design and in the construction (so that their insurance will compensate them), even in situations where there may be deficient maintenance of the properties.

Building administrators should have the data related to the materials and construction systems existing in their buildings, as well as data on factors that could accelerate building degradation and reduce the expected service life in their specific environmental conditions (Daniotti and Spagnolo 2007). This research can help to recognise the failures that lead to a reduction in the conditions of use in external walls.

In Spain, some insurance companies are planning to charge different fees according to the specific failures that exist in a building. That selective amount, with varying compensations, would be applied based on what would be the usual manifestation of a specific problem, and of the greater or lesser impact that the problem might have for owners. The issue that insurance companies have is finding a database that studies the damages in external walls, and that, in addition, is sufficiently reliable. According to the authors' understanding, the present research can be the starting point for this corporate-commercial process, given that it meets the criteria of comprehensiveness, total representation, and characterisation according to climate-geographical areas.

4.2.- Particular considerations

The reflection that we make on the existence of intermediate rainfall that obtains a higher percentage with respect to some others with high intensity, is that the result must be read together with the rest of the parameters that intervene in that strip. In places where there is a frequent cycle of rainfall and subsequent drying with high temperatures, is more aggressive than having a continuous rainfall, distributed over time and with the same temperatures.

The results obtained could be of interest for a government agency to create a national construction database to identify and expose which are the most common failures according to the different construction elements.

The authors want to underline the particular Spanish context regarding legal procedures. Within the warranty period, owners can file legal lawsuit, to the point that there are many lawyers and solicitors who have specialized in such lawsuit and often offer their clients this possibility to obtain insurance money, etc. This is so because all the buildings were recently built and were in the guarantee period (≤3 years old at the time of filing the lawsuit).

4.3.- Reflection on the process of execution

It was found that the different failures studied can occur as a result of irregularities or deficiencies during the construction works. Quality control during the execution of the works is fundamental so as to prevent cases that lead to problems during the service life of the external walls. Indeed, it was found that these situations can very frequently lead to cracks or humidities issues. Figure 5 shows some photographs that visually depict some of these deficiencies.

[FIGURE 5 HERE]

4.4.- Main innovations, achievements, and novel contributions of this research

The main innovations and achievements of this research are:

1-Using a data source that is very difficult to access (judicial records).

2-Using the expert reports of those records to know the types of failures.

3-Associating the location of those cases to four climate-geographical variables.

4-Classifying and quantifying the results according to the corresponding frequencies obtained.

5-Noting that location and climate affect the appearance of construction failures.

6-Having done all of the above, and with these characteristics in the data handling, over an element that had not yet been thus studied: exterior brick walls.

The main novel contributions of this research are:

a) Having accessed and obtained 100% of the cases from 100% of the country, within the period of the study (and in the field and universe of study: judicial sentences). This is extraordinary, given that works on civil engineering and architecture usually cover partial samples which, in many cases, are limited in size.

b) Over 1000 cases are analysed, which confers robustness to the results.

c) The constructions that were analysed are not connected between one another (for example, they are not from the same developer or builder), which strengthens the validity of the independence of the results, eliminating any bias.

5.- CONCLUSIONS

Scientific studies in the construction field based on court proceedings are practically non-existent – and those based on final sentencing are even fewer in number. This is due to the difficulty in accessing those sentences and in obtaining 100% of all the cases existing in a country, through the expert reports in which those sentences were based. Despite this difficulty, the present work is based precisely on such judicial sources. In order to collate analogous situations, a review was carried out of the international scientific literature, and no precedents were found in any other country. For this reason, it was not possible to compare the results, given that the sources, methodology, and amplitude of the data make this study a pioneer and unprecedented in its subject, the external brick walls of dwellings (through their climate-pathology distribution).

Based on the observations made from the judicial records analysed, the affinity group with the highest number of cases is the group of failures by humidity (HFG= 58%). In turn, the individual type of failure with the highest recurrence is 'humidity by infiltration' (287 cases) followed by 'humidity by condensation' (215 cases).

In relation to the finishing variant, facing walls have the most issues (W1= 717 cases). With regard to dwelling typology, most issues were found in apartment blocks (661 cases).

It was observed that, individually, the most problematic classes of climate-geographical variables are: the situation, close to the coast and in the north latitude. When combining in pairs, it was noted that the combinations with the highest percentages are situated in the strips of climatic location ‘Coastal-North’, with 46.21% of cases, and ‘Coastal-Mediterranean’, with 37.97% of cases.

Once the variables are joined together, and their normalised relative frequency is calculated, the highest concentration of construction failures in Spain in external brick walls occurs in AREA 1 (%CF> 18), which corresponds to buildings situated in coastal areas to the north of the country (be it with intermediate or high rainfall, and be they close to the Atlantic or to the Mediterranean).

In future studies, it would be of interest to correlate construction failures with other parameters. An attempt could be made of incorporating the exact GPS location of each building. This was not possible in this study given that this information is not present in the expert reports – and due to the limitation, that was set, of preserving confidentiality and protecting certain information related to the persons that filed the judicial complaints. If other researchers in some countries could have access to this sensitive information, it would be interesting to correlate it with other external parameters not contained in the judicial process, as well as with those that are indeed contained therein. All these parameters should be processed for each of the more than one thousand cases studied, which gives an idea of the great difficulty in achieving and quantifying all these concepts. Nevertheless, should these difficulties be overcome, in a future stage of research it could be considered to create an interactive map showing the results of each of the variables, the values of %PC according to the 39 existing Strips of Climatic Location, as well as the normalised frequencies of Areas 1, 2, 3, and 4.

Given the configuration and characteristics of the methodology used, designated as “climate-typological interrelation of failures according to court records” (CTIF-ACR), the methodology can be extrapolated to other places and climates, since once the court records have been obtained, they need only be associated to the corresponding climate variables.

These results may be of interest to architects and engineers, but also to developers, construction companies, and insurance companies.

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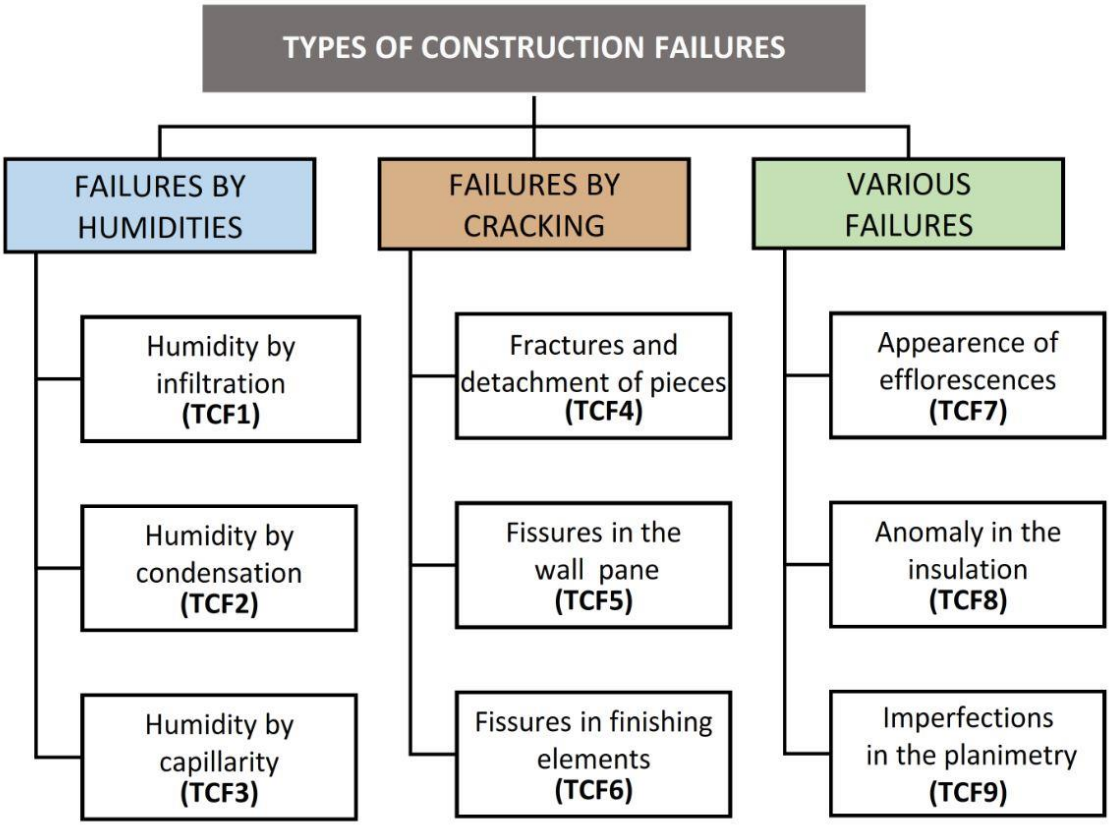

Figure 1 – Types of construction failures found

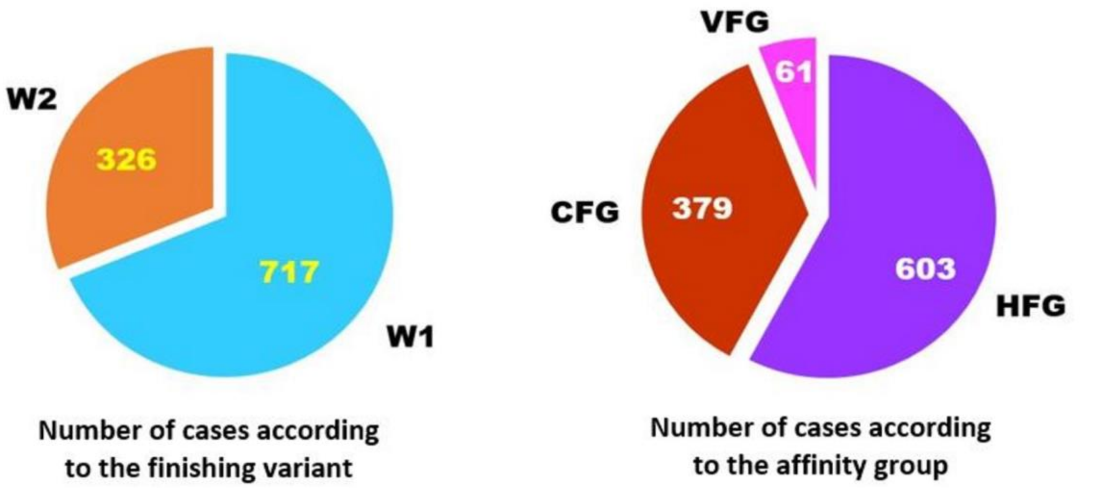

Figure 2 – Distribution of cases according to the finishing variant and the affinity group

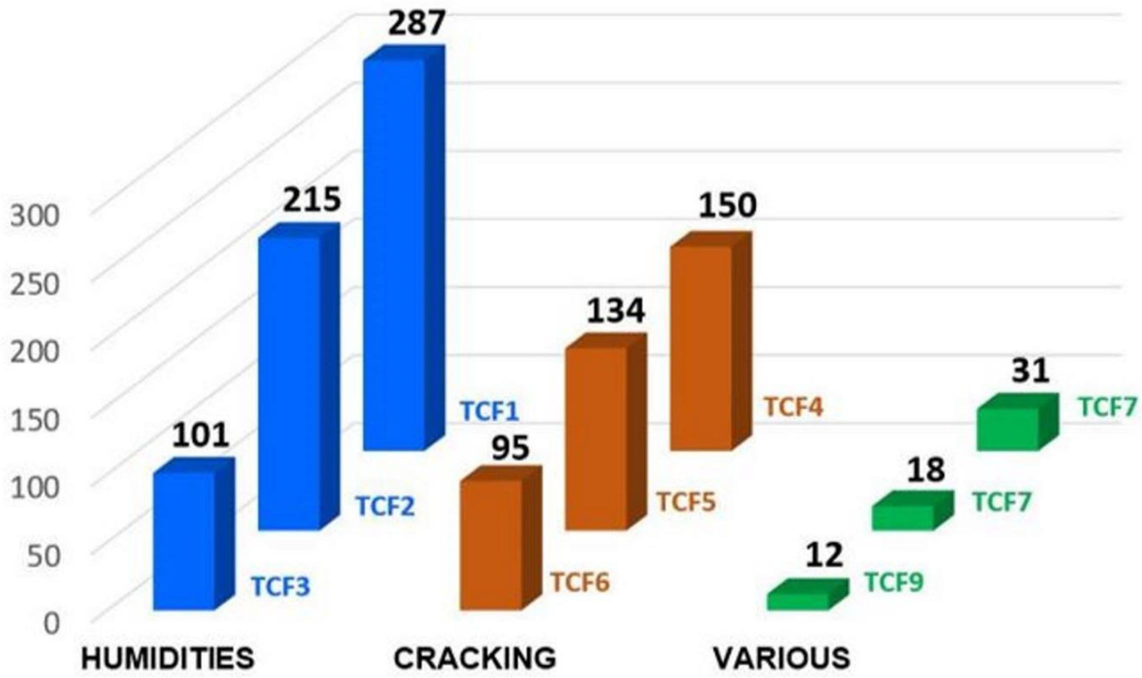

Figure 3 – Number of cases by type of construction failure

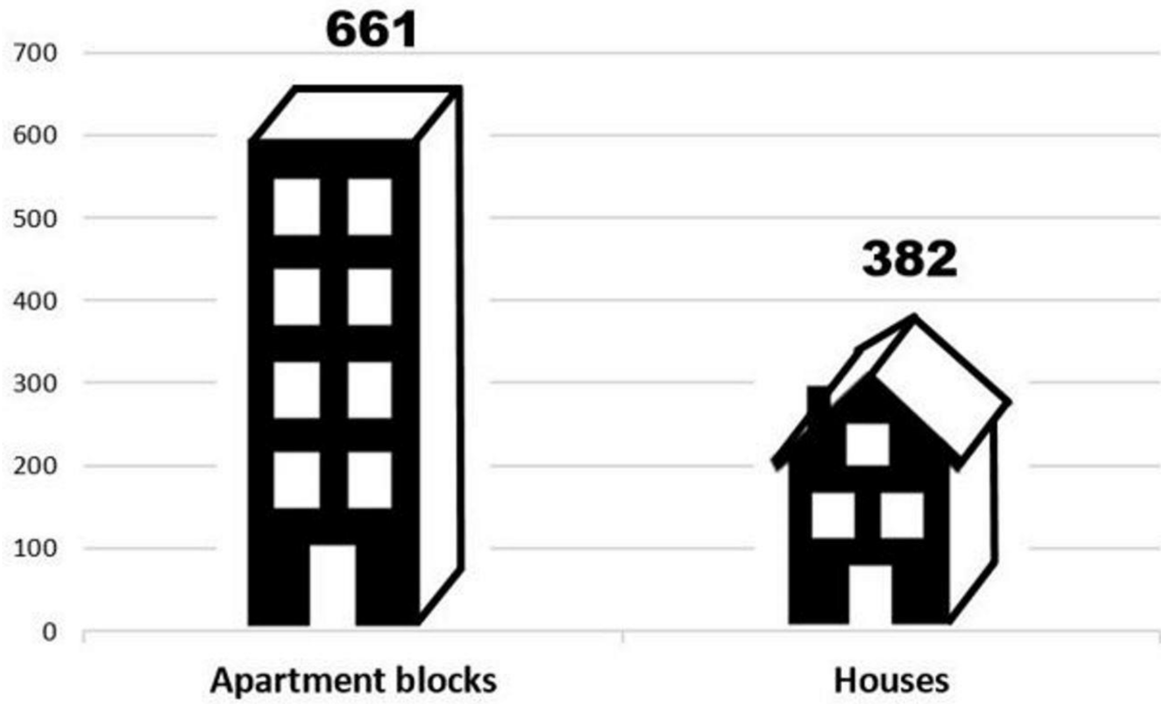

Figure 4 – Number of cases according to dwelling typology

Vertical fissure in the tail-end between one part of a wall with the corner of the building. The fissure appears in the brick cover of the concrete pillar, which is of lower thickness than the rest of the external wall.

Lateral view of the jamb of an opening in a facade. A separation can be seen between the brick and the aluminium window frames. Water can enter this gap, and lead to humidities on the inside.

Tail-end in corner of two facing walls (angle of tail-end different to 90°). As the bricks were not cut into a continuous edge, water and snow can accumulate on the surfaces.

Insufficient number, distribution, and penetration of bond bricks. This situation can later lead to fissures, due to the lack of interlocking between the bricks.

Images by Manuel J. Carretero-Ayuso

Figure 5 – Photographic examples of several execution problems

Table 1 – Phases and stages of the process of research into exterior brick walls

PHASE	STAGE	CONCEPT
A	1	Knowledge of the existence of cases through the civil responsibility insurance of technical architects
	2	Request to the insurance company to provide us with the references of each lawsuit
	3	Provision, by the manager of the insurance company, of a list with the references of each lawsuit
	4	Request to the Justice Administration to gain access to the records of each lawsuit in that list
	5	Authorisation by the Justice Administration to gain access to those judicial records
	6	Verification that the cases had received final sentencing (i.e., that the sentence was unappealable)
B	7	Detailed reading of the judicial records and of the expert reports contained within them
	8	Identification of the building typologies with complaints related to problems in their walls
	9	Noting the location of said buildings
	10	Identification of the different types of failures according to their type
	11	Creating of the three groups of failures according to their affinity
	12	Verification of the finishing variant of each case
	13	General count of cases for each of the intervening parameters
	14	Assignment of cases to their corresponding climate-geographical variables, according to their location (as per Table 2)
	15	Total characterisation of the population of cases studied (Table 3)
C	16	Obtaining the results by finishing variant and affinity group
	17	Obtaining the results by type of construction failure
	18	Obtaining the results by building typology
	19	Climate-geographical study. Distribution of failures according to climatic variables
	20	Climate-geographical study. Determination of strips of climatic location
	21	Climate-geographical study. Specification of areas by ranks of normalised frequencies
D	22	Discussion. General considerations
	23	Discussion. Reflexions on the execution process
	24	Production of the terminology and definitions
	25	Conclusions

Table 2 – Classes according to climate-geographical variables

VARIABLES		CONCEPT	CLASSES			
Climate-geographical	A	Situation	Coastal	Interior	---	---
	B	Latitude	North	Central	South	---
	C	Climate	Oceanic	Continental	Mediterranean	Subtropical
	D	Annual Rainfall	Low <450mm *(17.7 in.)*	450mm *(17.7 in.)* ≤ Intermediate ≤ 700mm *(27.6 in.)*	High >700mm *(27.6 in.)*	---

Table 3 – Characterisation and number of cases according to each climate-geographical variable, finishing variant and dwelling typology

VARIANT AND TYPOLOGY		SITUATION		LATITUDE			CLIMATE				ANNUAL RAINFALL			Sum by Typology
		CS	**IS**	**NL**	**CL**	**SL**	**OC**	**CC**	**MC**	**SC**	**LR**	**IR**	**HR**	
W1	**Apartments**	343	92	300	72	63	183	72	160	20	52	204	179	435
	Houses	192	90	166	68	48	44	79	145	14	55	188	39	282
	Subtotal	535	182	466	140	111	227	151	305	34	107	392	218	717
W2	**Apartments**	123	103	158	52	16	54	99	69	4	45	128	53	226
	Houses	55	45	62	25	13	20	44	35	1	20	60	20	100
	Subtotal	178	148	220	77	29	74	143	104	5	65	188	73	326
Total	**Apartments**	466	195	458	124	79	237	171	229	24	97	332	232	661
	Houses	247	135	228	93	61	64	123	180	15	75	248	59	382
	Subtotal	713	330	686	217	140	301	294	409	39	172	580	291	1043
Global		1043		1043			1043				1043			---

Note: CS: Coastal Situation; IS: Interior Situation; NL: North Latitude; CL: Central Latitude; SL: South Latitude; OC: Oceanic Climate; CC: Continental Climate; MC: Mediterranean Climate; SC: Subtropical Climate; LR: Low Rainfall; IR: Intermediate Rainfall; HR: High rainfall; W1: Cladded walls; W2: Facing walls

Table 4 – Percentages of presence of the failures in the external walls according to each variable of climatic location

VARIABLE / LOCATION			STRIP OF CLIMATIC LOCATION	%PC	% TOTAL
WITH A SINGLE VARIABLE	SITUATION		Interior	31.64%	Variable A
			Coastal	68.36%	
	LATITUDE		North	65.77%	Variable B
			Central	20.81%	
			South	13.42%	
	CLIMATE		Oceanic	28.86%	Variable C
			Continental	28.19%	
			Mediterranean	39.21%	
			Subtropical	3.74%	
COMBINING VARIABLES IN PAIRS	SITUATION-LATITUDE	INTERIOR-LATITUDE	Interior-North	19.65%	Variable A + Variable B
			Interior-Central	9.78%	
			Interior-South	2.30%	
		COASTAL-LATITUDE	Coastal-North	46.21%	
			Coastal-Central	10.94%	
			Coastal-South	11.12%	
	SITUATION-CLIMATE	INTERIOR-CLIMATE	Interior-Oceanic	2.40%	Variable A + Variable C
			Interior-Continental	28.18%	
			Interior-Mediterranean	1.15%	
		COASTAL-CLIMATE	Coastal-Oceanic	26.56%	
			Coastal-Mediterranean	37.97%	
			Coastal-Subtropical	3.74%	
	LATITUDE-CLIMATE	NORTH-CLIMATE	North-Oceanic	28.95%	Variable B + Variable C
			North-Continental	17.26%	
			North-Mediterranean	19.65%	
		CENTRAL-CLIMATE	Central-Continental	9.78%	
			Central-Mediterranean	10.94%	
		SOUTH-CLIMATE	South-Continental	1.15%	
			South-Mediterranean	8.53%	
			South-Subtropical	3.74%	
COMBINING 3 VARIABLES	COASTAL	NORTH	Coastal-North-Oceanic	26.56%	Variable A + Variable B + Variable C
			Coastal-North-Mediterranean	19.65%	
		CENTRAL	Coastal-Central-Mediterranean	10.93%	
			Coastal-South-Mediterranean	7.38%	
		SOUTH	Coastal-South-Subtropical	3.74%	
	INTERIOR	NORTH	Interior-North-Oceanic	2.40%	
			Interior-North-Continental	17.26%	
		CENTRAL	Interior-Central-Continental	9.78%	
		SOUTH	Interior-South-Continental	1.15%	
			Interior-South-Mediterranean	1.15%	

Table 5 – Classification by ranks of climate-geographical areas sorted by intensity of presence with 3 variables

SITUATION-LATITUDE-CLIMATE	%PC	TOTAL %PC	RELATIVE FREQUEN. ($x10^{-5}$)	STANDARDISED RELATIVE FREQUENCY	CLIMATE-GEOGRAPHICAL AREA	RANK OF PATHOL. CONCENTR.
Coastal-North-Oceanic	26.56%	46.21%	3.93	1.00	**AREA 1**	**%CF > 18**
Coastal-North-Mediterranean	19.65%					
Interior-North-Continental	17.26%	28.19%	3.09	0.79	**AREA 2**	**10 < %CF ≤ 18**
Coastal-Central-Mediterranean	10.93%					
Interior-Central-Continental	9.78%	17.16%	0.95	0.24	**AREA 3**	**5 < %CF ≤ 10**
Coastal-South-Mediterranean	7.38%					
Coastal-South-Subtropical	3.74%	8.44%	1.43	0.36	**AREA 4**	**%CF ≤ 5**
Interior-North-Oceanic	2.40%					
Interior-South-Mediterranean	1.16%					
Interior-South-Continental	1.14%					

Table 6 – Classification by ranks of climate-geographical areas incorporating annual rainfall as a fourth variable

SITUATION-LATITUDE-CLIMATE-ANNUAL RAINFALL	%PC	TOTAL %PC	RELATIVE FREQUEN. ($x10^{-5}$)	STANDARDISED RELATIVE FREQUENCY	CLIMATE-GEOGRAPHICAL AREA	RANK OF PATHOL. CONCENTR.
Coastal-North-Oceanic-High	26.56%	46.21%	3.93	1.00	**AREA 1**	**%CF > 18**
Coastal-North-Mediterranean-Intermediate	19.65%					
Interior-North-Continental-Intermediate*	11.98%	22.91%	3.15	0.80	**AREA 2**	**10 < %CF ≤ 18**
Coastal-Central-Mediterranean-Intermediate	10.93%					
Interior-Central-Continental-Intermediate*	7.67%	18.32%	1.26	0.32	**AREA 3**	**5 < %CF ≤ 10**
Coastal-South-Mediterranean-Low*	5.37%					
Interior-North-Continental-Low*	5.28%					
Coastal-South-Subtropical-Low	3.74%	12.56%	1.13	0.29	**AREA 4**	**%CF ≤ 5**
Interior-Central-Continental-Low*	2.11%					
Coastal-South-Mediterranean-Intermediate*	2.01%					
Interior-North-Oceanic-High*	1.35%					
Interior-South-Mediterranean-Intermediate	1.16%					
Interior-South-Continental-Intermediate	1.14%					
Interior-North-Oceanic-Intermediate*	1.05%					

* *Subdivisions of the AREAS climate-geographical that appear when incorporating annual rainfall as a fourth variable*