Sustainable building repair: A K-means approach to addressing fissures in ceramic brick partition walls

Highlights:

- This study is based on final, unappealable, 603 cases of court sentences.
- Includes the failures detected in ceramic brick partition walls in Spain for 10 years.
- A procedure has been designed to determine the risk of filing demands.
- The environmental impact of repairing the most common cause has been assessed.
- This study has impact in the long term on the reduction of maintenance operations.

Abstract

The purpose of this work is to determine, catalogue, and quantify failures appearing in ceramic brick partition walls after the delivery of buildings, based on claims filed by users and on the philosophy of 'learning from failures'. To examine the more than 600 cases presented, technical affinity groups were defined for the descriptors used, a series of checks were carried out using cluster analysis, a proprietary procedure was implemented for calculating the risk of demands being filed, and a final risk assessment process was made, divided into five categories. It was found that there is a recurring presence of large cracks due to incorrect bond/connections between brick wall panels. The repair of the most frequent cause of 'Incorrect lock/connection of the panes' was analysed in terms of CO2 emissions. The study of a large number of real cases, such as has been done in this paper, can allow us to advance and define new strategies to significantly minimise future failures, making it difficult for them to reach the usage phase of the building. The access to a type of data source never before used in the world to corroborate the types of damages and causes that occur in partitions (indicating their recurrence and evaluating user dissatisfaction) is unprecedented.

Keywords

Forensic engineering
Pathologies
Sustainability
Bricks
Interior walls
Courts

1. Introduction

1.1. Generic context

The fabrication and utilization of ceramic bricks in construction is quite an old practice. They are made with a homogenous mix of clay and water that constitute a paste. This paste is compressed through moulds to be subsequently baked in ovens. The existence of clay in locations around the globe has facilitated its use as a construction material worldwide [1,2]. Ceramic bricks are used to build external and internal walls, and these can be raised with pieces of different shapes and characteristics (solid, solid but lowered in its surface, cored, hollow – double hollow, single hollow, …) and of different sizes and thicknesses. Nowadays, internal partition walls often have hollow bricks (with horizontal holes) since their main function is that of dividing internal spaces, not requiring to have any significant resistance. These partition walls are normally coated on both sides with plaster or with cement mortar [3].

1.2. Selection of some of the studies that were reviewed

Ceramic brick masonry walls have been substantially studied over the years – be they made with traditional ceramic bricks [[4], [5], [6]] or with innovative solutions using new materials [[7], [8], [9]]. Environmental questions have also been considered, and several works examine the reuse of brick waste [10]. Most existing studies pertain to laboratory analyses [11,12] or computational models [13,14], in which performance improvements are studied. On the contrary, there are not many studies focusing on real cases [15,16], or on this solution's actual construction (either its commissioning or to any of its anomalies). In other words, the vast majority of existing research focuses more in the study of the constituent materials themselves (sometimes in combination with other materials), through their physical, chemical, or mechanical characterisation [[17], [18], [19], [20]].

However, a building does not function as a mere sum of separate materials. Connections between materials lead to the building functioning as a whole. The novel contribution made by this study is that of presenting results on the constructed element (partition walls) in buildings being currently used, rather than being focused on what the wall is made of (bricks or cement mortar) or on portions of the element (parts of a wall). In addition, the study is conducted with respect to interior partitions and not on facades [21].

2. Problem definition

2.1. General problems in brick masonry walls

The brick is a cheap and accessible material. Its performance when compressed is satisfactory, though that is not the case with tension [22] or shear [23]. As with any material, it is not exempt from the appearance of problems. Among the different general conceptual reasons behind failures in ceramic brick masonry walls (be they in facades, interior distribution and partition walls, brick load-bearing walls, brick retaining walls, exterior brick enclosures, etc.) are those mentioned in the following paragraphs.

Differential settling: it occurs when there are occasional alterations in the stability of adjoining soils; normally due to the lack of resistance of the soil [24], the erosion of finer particles due to water infiltrations, nearby excavations [25,26], or by liquefaction caused by earthquakes [27,28]. It can also occur as a result of changes in the foundations [29]. When differential settling occurs, rigid and slender construction elements tend to be the most effect, such as partition walls, there appearing cracks in them.

Infiltrations: many water installations are placed next to brick masonry walls, or even embedded in them. In order to guarantee that connections are done correctly, pressure tests should be done before covering the piping, to ensure no water leaks and there is no obstruction in the circuit. This type of test is not always carried out, so issues are found only when residents begin using the properties – requiring subsequent repairs [30]. Places such as kitchens and bathrooms are areas in which much water is used, and the detailed design of their water installations is thus essential to minimise leaks [31].

Spots caused by condensation humidity: when there are compartments with high percentages of humidity, such as bathrooms and kitchens, without any openings to the outside and/or without adequate ventilation, mould begins to appear. Ventilation is an effective method to eliminate humidity in internal rooms [32,33], and when it is not correctly done there begin to appear condensation problems.

Efflorescences and cryptoefflorescences: when unprotected, masonry elements located on the ground floor can display salt deposits in their lower areas, due to water rising through capillarity and carrying these salts from the ground or from other construction materials. This mechanism has been studied extensively [34,35]. When arriving at the surface, the water evaporates, but the salts remain on the outer face. This type of phenomenon can be addressed by preventing water from rising through the brick masonry walls. This depends on several factors, such as [36] the environmental conditions, the insulation, the presence of salts, the thickness of the wall, as well as the porosity and the porometry of the materials.

Fissures: variations of temperature or retraction (or even mechanical actions), can lead to fissures that tend to appear in the narrower sections, or sections that have discontinuities. In the case of ceramic masonry elements, they tend to occur mainly in horizontal and/or vertical joints between bricks [37].

Deformations of the plane beyond the vertical axis: brick masonry walls should be occasionally tied to structural elements such as pillars, through specific connecting elements. This requirement is often either omitted by designers or not followed by builders. After some time, specific loads affecting the structure may lead to one of the sides shifting positions [11,38]. These types of deformations can be exacerbated in the event of an earthquake. Masonry walls play a crucial role as they act as bracing elements during seismic events. The connections between these walls and the structure become essential. Experimental studies, such as those conducted by Tomić et al. [39], demonstrate how the testing of real-scale solutions in a reduced model can simulate the behaviour of a specific structure within a relatively brief time period. These tests can then be compared with the results of computational models and help calibrate these models. In this way, engineers can better simulate the behaviour of this type of constructive solutions. These simulations can include a vast amount of data. This big data with the help of the artificial intelligence can be applied to computational engineering, as discussed by Babović et al. [40]. These authors also highlight the potential areas for future research in the computing field.

2.2. Sustainability and CO2 emissions in repairs

In masonry walls can appear fissures which are a common problem in construction and can be caused by several factors, including errors in the connection between walls, ceilings, and floors. The formation of fissures in masonry walls is a common issue that can occur due to various reasons [41]. Recent studies, such as [42], show that the lack of proper connections between different building elements is one of the primary causes of fissures in masonry walls. The use of metal connectors [43] and the traditional technique of opening a groove and replacing the plaster, are some of the methods for repairing these kind of fissures that have been proposed in the literature.

These repairs due to bad construction practices have costs and increase the carbon emissions of the construction. There are many articles [[44], [45], [46]] that discusses the importance of mitigating carbon emissions in the construction, highlighting the need for sustainable building practices. The use of low-carbon alternatives is crucial for diminish carbon emissions in the construction [47]. The ideal is to have buildings that use more natural materials, which can be reused and recycled, in order to have a smaller ecological footprint and, consequently, lower CO2 emissions [48]. The adoption of sustainable building practices into the design and construction phases of building projects can lead to significant environmental benefits, such as reduced carbon emission.

2.3. Relevance of this research

The authors have provided in the previous sections an indication of the overall framework regarding the subject matter addressed in this research, a selection of previously published articles, and a definition of the problem. However, did not find papers that document the most recurrent construction failures and the ones that caused the greatest dissatisfaction to users within the construction unit related to ceramic brick partitions. To know them with certainty, one must resort to the most energetic, forceful, and traumatic process that demonstrates a person's dissatisfaction: a lawsuit before the courts of justice. This research gap is covered by this scientific publication, which represents a original and significant contribution of knowledge and a novelty in forensic engineering. The access to a type of data source never before used in the world to corroborate the types of damages and causes that occur in partitions is unprecedented in the international literature.

To characterize the descriptors involved in these construction failures (types of damages, causes, and buildings), a novel methodology for this construction unit was used, which includes verifying similarities through cluster analysis with k-means and a 5-phase evaluation method. The ad hoc procedure used is called "Typological and numerical relation of pathologies according to judicial sentences".

3. Methodology

Based on the anomalies that appeared in the ceramic brick partition walls studied, the methodology and work procedure that were developed, intend to:

- Create groups based on technical affinity of damage types and causes.
- Use cluster analysis to identify sets of cases that are mathematically similar.
- Quantify the frequency of damage types in different types of buildings.
- Develop an evaluation method for existing cases.
- Create a risk categorisation process based on claims data.
- Calculate the numerical risk factor based on the interrelationships obtained.
- Calculate the CO2 emissions for the most frequent cause.

3.1. Data source

The documental basis from which the technical information for this research is extracted has its origin in the files of the civil liability insurance of Spanish building engineers and technical architects [49]. Those judicial files were selected due to the filing of demands by building users against agents participating in the construction process, as a result of failures existing in construction elements in the buildings – namely, in this case, in internal partition walls. The failures detected between the years 2008 and 2017 and which resulted in subsequent demands were considered in this study [50]. In order to be able to include cases in the research, an additional condition was set, that the demands in question were already

concluded and unappealable (their sentence was final and could not be appealed/sent to higher courts). In some cases, this additional condition took a number of years to be met.
A significant amount of data has been handled, assessed, and examined. A total of 603 cases (see Fig. 1) were extracted as bearing relation with buildings' ceramic partition walls (of hollow bricks). In general, the technical documentation was organised according to the structure outlined in UNE-41805-10 standard [51] for the preparation and drafting of pathology reports (antecedents, data collection process, observation, inspections carried out, interpretation of results, etc.).

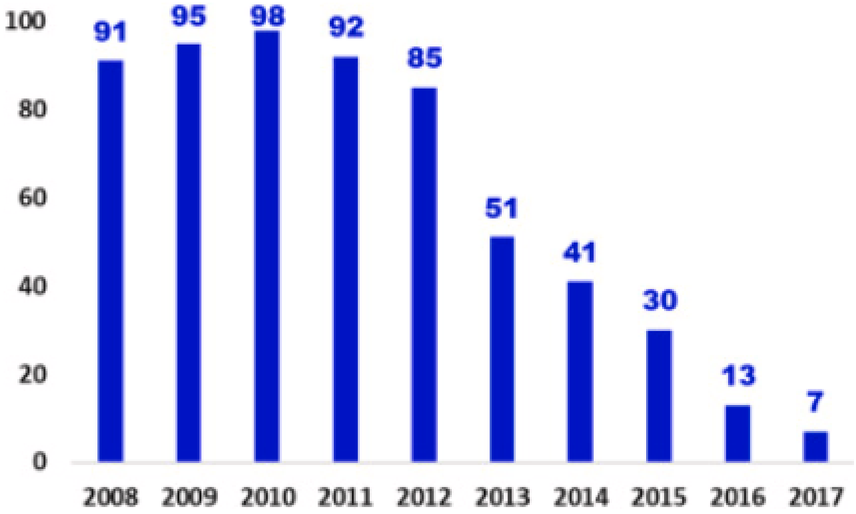


Fig. 1. Number of case studies per year.

All the data on which this study is based is taken from expert reports that were included in said demands. It has then been grouped, categorised and mathematically analysed, as described in the following chapters. It should be noted that these expert reports were requested by the company of civil liability insurance of the professionals and technicians participating in the works (and who were subsequently sued), due to the appearance of construction failures during the warranty period of buildings.

The method used in this research is not a '"case study" (It does not focus on a specific building case or on a limited area with preselected characteristics), nor an "experiment" (it is not an empirical proof in order to analyze its effects), and also not a "specific survey" (the data has not been obtained through a previously-created questionnaire). It is an analysis of the census carried out on the whole population of these elements in Spain (under the principle of simultaneity and totality). In other words, 100% of the existing data in the indicated 10-year period has been verified in each and every region of the country.

It is both exceptional and significant that the data of a given study should correspond to the entirety of the cases existing both the time period and in the country in question. In this regard, this study is both detailed and complete. It can also be noted that no prior research was found by other authors on ceramic partition walls with a methodology and data source similar to those presented herein. This methodology is adjusted to the specific characteristics of the data used (sentences of the Administration of Justice of the Spanish State) and has been named 'Typological and numerical relation of pathologies according to judicial sentences'.

The number of construction failures shown in the research is much higher than the numbers usually included in much of the scientific research of the past two decades. In said international literature, it is noticeable that a significant number of studies on construction failures primarily concentrate on buildings associated with a single developer or construction company, or are related to surveys based on them. In this paper, however, there are no parameters that can interrelate the cases in between them; this ensures the independence of the results that are shown later in the study.

3.2. Constructive characteristics of the partitions

The set of partitions that are part of this study is very homogeneous. They have a base thickness of 7 cm or 7.5 cm for a double hollow ceramic brick partition set with cement and sand mortar. On both sides, the partition is coated with a 1.5 cm nominal thickness plaster. Therefore, the partition has a total thickness of 10 cm. These bricks always have 6 square perforations horizontally (with lateral openings on both sides), with dimensions of 24 cm (length) x 11.5 cm (height) x 7 cm (width), although according to manufacturers, the dimensions can vary ±0.5 cm in length and height, as well as +0.5 cm in width. The height of the partitions was usually between 2.5 m and 2.7 m.

3.3. Descriptors used

The fundamental concepts on which this research has been based were named descriptors. These are ‘types of damages’, ‘types of causes’ and ‘types of buildings’, which between them contain a total of 25 different concepts. Moreover, within the two first descriptors are the concepts they contain, forming ‘technical affinity groups’ (AG), of both damages (D.AG) and causes (C.AG), according to the similarities between them. Their name and hierarchical structure are shown in Table 1.

Table 1. Organizational structure of the descriptors, of their technical affinity groups and of the concepts of which they are composed.

Descriptor	**Technical affinity group**	**Code**	**Concept**
Types of Damages	Effect of fissures D.AG-F	D1	Fissures originating in the construction
		D2	Fissures in the finishing
	Effect of humidities D.AG-H	D3	Humidities by condensation
		D4	Rising damp
	Diverse effects D.AG-D	D5	Incorrect flatness of the faces of the partition wall
		D6	Existence of spots or dirt
Types of Causes	Conditions due to incorrect placement C.AG-I	C01	Incorrect lock/connection of the panes
		C02	Incorrect joining of the carpentry
		C03	Incorrect process of verticality
		C04	Incorrect execution of grooves
	Conditions due to absences and deficiencies C.AG-A	C05	Deficiency or absence of ventilation
		C06	Deficiency or absence of cladding in structural elements
		C07	Deficiency or absence of construction or expansion joints
		C08	Deficiency or absence of barrier against capillary moisture

		C09	Deficiency or absence of thermal insulation
	Conditions pertaining to materials C.AG-M	C10	Characteristics and nature of the material utilized
		C11	Low adhesion to base
		C12	Incorrect anchoring material
		C13	Unsuitable breast beams
	Conditions for meeting between elements C.AG-C	C14	Lower terrain in direct contact
		C15	Presence of phreatic level
		C16	Attack by moisture
Types of Building		B1	Apartment buildings
		B2	Houses
		B3	Other buildings

It is evident that this table does not include all possible types of damages and types of causes that can occur in a general and conceptual way in this construction unit. However, it should be noted that only those cases that were brought before the Spanish judicial system are included here. Therefore, it is not a catalog that shows the full range of possible situations; it only includes those that filed a demand.

3.4. Cluster analysis for one of the descriptors

3.4.1. Algorithm used: k-means

To carry out the cluster analysis on one of the descriptors, -means was applied. This is an iterative reallocation clustering method based on the association of individuals by centroids [52]. The method takes a set X of n individuals to be classified into k associations, for which is considered a partition W of that set with W = (w1, …, wa, …, wb, …, wk), such that $(U_{a=1}^{k} w_a = X, w_a \cap w_b = \emptyset, a \neq b)$, ensuring that the sum total of the squared Euclidian distances within each association is minimised –Eq. (1)–:

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

Where μ_{ar} is the value of the centroid and x_{ir} is the value of the dataset observations.

The algorithm depends on the initial centroids and can lead to different results when the initial settings of k are changed. Thus, the larger the value of k used in the method, the smaller the oscillation within associations (i.e., the more individual associations are created). In the event that the variables have different units (as in this study), a data normalization preprocessing should be performed. This normalization should be done before applying k-means.

3.4.2. Hyperparameters considered in the cluster analysis

The data set used was normalized between 0 and 1 to obtain proper rankings. The number of clusters analysed ranged from 2 to 10. For an adequate selection of the number of associations, 3 submethods were considered in this investigation. These submethods were: the elbow rule, the silhouette coefficient (s(i)), and the ratio between sum of squares and total sum of squares (BSS/TSS).

The elbow rule allows selecting the appropriate number of groups by minimizing the total sum of squares (WSS) [53]. This rule consists of the following stages: (i) k-means is used with different numbers of groups; (ii) WSS is calculated in each group –Eq. (2)–; (iii) the WSS curve is drawn; and (iv) the position of the elbow on the chart is generally considered an approximation of the proper number of clusters.

$$WSS = \sum_{k=1}^{K} \sum_{i \in S_k} \sum_{j=1}^{p} \left(\overline{x}_{kj} - x_{ij}\right)^2 \qquad (2)$$

Where xkj is the j-th variable of the centre of the group, and Sk is the set of associated observations in the k-th cluster.

BSS/TSS was also evaluated. It describes the compactness of associations in a percentage from 0 to 100%. The higher the value of the relationship, the greater the compactness of individuals within an association. Similarly, since TSS=BSS + WSS, the higher the BSS, the lower the WSS. The formula –Eq. (3)– for the ratio is:

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

Where xG is the pooled mean of each association.

Finally, s(i) was used. This indicator is very useful in cluster analyses, with wide use in several studies [54]. The index obtains the resemblance of an observation with the other observations of the same association. Therefore, the indicator shows the quality of an association. To obtain s(i), the following equation –Eq. (4)–:

$$s\left(i\right) = \frac{b(i) - a(i)}{max\{a(i), b(i)\}} \qquad (4)$$

Where, a(i) is the mean distance between observation (i) and the other observations of the same association; and b(i) is the smallest distance between the observation and the others associations. s(i) can get results between −1 and 1, with ideal results between 0 and 1.

3.5. Design of the evaluation method

The research considered carrying out two stages: a first stage named ‘design of the method’ (within which 4 phases were established) and a second stage named ‘process of categorisation’ (with just one phase).

The first phase of the first stage consisted in consulting 10 expert arbitrators to carry out an ‘inter-arbitrator validation’, according to the Delphi procedure and reference standard ‘UNE EN 31010’ [55]. In order to be selected as an expert arbitrator in this context, individuals with over 20 years of labor occupation and direct intervention in the analysis and resolution of construction failures were identified. With the goal of obtaining a comprehensive and multifocal vision, people with diverse trajectories were sought (professors of technological universities, specialists in liability insurance, quality process supervision technicians, judicial experts, etc.).

The first decision made by these expert arbitrators was that a score would be applied to the technical affinity groups, both of damages and of causes. For the affinity groups of damages, the score was founded on the discomfort degree or perceived dissatisfaction that user could have as a result of the characteristics of the group of damages itself (the expert arbitrators, following an analysis, determined that this score should be odd: 1; 3; 5). As for the affinity groups of causes, the score was based on the degree of technical importance that each group of causes represented (the expert arbitrators determined that this score should be even: 2; 4; 6; 8).

From the decisions mentioned above and from the level of presence of these technical affinity groups, a 4-phase procedure was established (within the already-mentioned first stage) to quantify the importance of the existing interrelationships, until different ‘categories of risk’ were arrived at for users' complaints. This is, until the probability of filing a judicial complaint according to the nature of each intervening parameter and to the recurrence of the occurring interrelationships could be determined.

Phase 1- Ranking according to the degree of problem: It provides the individual value of the affinity group of damages (D.AG) and the affinity group of causes (C.AG). This phase is divided in the following subphases:
Subphase 1A – The concept of ‘possibility of appearance’ of a construction failure was indicated from UNE 60812 standard [56] for assignment to the affinity groups. It should be noted that said regulation acknowledges that there is no general and single definition to assign a ‘possibility of appearance’. For this reason, it is indispensable that those formulate the analysis and evaluation process (in this context, the expert arbitrators) establish a uniform framework for each situation, depending on the specialty and the field concerned. In this case, it would be: building construction > secondary work > partitions > partition walls of ceramic bricks > existence of damage > risk of occurrence of these damages > risk assessment from a judicial complaint perspective. Thus, the discomfort degree or perceived dissatisfaction from the users' perspective resulting from different types of damages in their buildings (in this case joined together by affinity groups) was assigned by the expert arbitrators. This assignment was carried out in accordance with their professional work considerations and experience, but also depending on the properties of said groups of damages and problems of habitability or use that made users more or less likely to file a judicial complaint. This process was done without them knowing the final values of the results obtained in the data collection.

Subphase 1B – the classification of classes described in the above-mentioned UNE standard to delimit the possibility of appearance of a construction failure (frequent, probable and occasional) was related to the score mentioned above: 5, 3 and 1 points, respectively (process of association of a concept-theoretical scale to a numeric scale). In order to achieve this, the ‘weighted factors method’ was referred to, with the necessary adaptations. In this way, the concepts that participate and that are valued are the nature of the affinity group (set D = {D.AG-F, D.AG-H and D.AG-D}) and the scale of the score to be applied (set P = {1, 3 and 5}). The value attribution procedure in the original weighted factor method is carried out by the directors of an entity or company, and in this situation, by the expert arbitrators, according to the following mathematical description:
Let ‘k’ be the number of affinity groups of damages to be scored (D.AG-F, D.AG-H and D.AG-D) and ‘q’ the number of expert arbitrators that will attribute the value, which we will designate B1, …,eq. For each 1 ≤ i ≤ q, the process by which the expert arbitrator ei assigns a certain score to the groups of damages is given by a bijective application ϕi:D→P. This is, ϕi(dj) identifies the score of the expert arbitrator ei to the damage dj. Thus, the condition of being bijective implies that each expert arbitrator must assign different scores to each affinity group of damages. The problem, then, is that of defining a bijective application ϕ:D→P from the family ϕ1, …,ϕq. This application shall be defined as a scores matrix A=(aij); this is, A is a matrix q × k, where

aij=ϕi(dj). In this way, aij is the score given by the expert arbitrator ei to the group of damages dj.

Subsequently, the average of the scores given by the expert arbitrators to the group of damages dj is obtained, where 1≤j ≤ k, as per the following expression –Eq. (5)–:

$$x_j = \frac{\sum_{i-1}^{q} a_{ij}}{q} \qquad (5)$$

Let us rewrite the succession x1, …,xk (averages obtained) from smallest to largest, as xj1≥xj2≥…≥xjk so that the values of the set P are assigned to each affinity group of damages according to the importance given by the global scoring of all the expert arbitrators.
Subphase 1C – All of the above-described was carried out in a mathematical way, analogous to the characteristics of the affinity groups of causes; in this case, with the scores 2, 4, 6 or 8.
Phase 2- Joint level of severity: it is composed of the numerical coupling of the rankings indicated for Phase 1. The values are included in the section two of the antepenultimate figure of the paper ('Establishment of the risk levels of user demands', titled 'Joint level of severity'). These are obtained by multiplying the score of each affinity group of damages by the score of each affinity group of causes.
Phase 3- Matrix of interrelationship and intensity: Calculation of each of the 36 combinations obtained from the different interrelationships between the 3 technical affinity groups of damages, the 4 technical affinity groups of causes and the 3 types of buildings. According to the level of presence of each interrelationship, we obtain the values of the general calculation of percentages that are expressed in the table of the chapter of results that break down the interrelationship between the three descriptors -Table 3- (which are integrated in the third section of the antepenultimate figure of the paper 'Establishment of the risk levels of user demands', titled 'Matrix of interrelationship and intensity'.

Table 2. Causes associated with each cluster and individual value of s(i).

Cluster	Cause	S(i)
Cluster 1	C01	0.0000000
Cluster 2	C05	0.5080018
	C06	0.6532663
	C07	0.6377953
	C02	0.4859438
Cluster 3	C08	0.6343490
	C03	0.7577236
	C04	0.7489771
	C09	0.1947500
Cluster 4	C10	0.6226310
	C14	0.8415525
	C11	0.8961474
	C15	0.8961474
	C12	0.8913380
	C16	0.8913380
	C13	0.8638393

Table 3. Matrix of relation between the technical affinity groups of damages and causes.

Causes	Damages		
	D.AG-F	D.AG-H	D.AG-D
C.AG-I	299 (49.6%)	–	35 (5.8%)

C.AG-A	105 (17.4%)	128 (21.2%)	–
C.AG-M	21 (3.5%)	–	–
C.AG-C	–	12 (2.0%)	3 (0.5%)

Phase 4- Demand risk weighted matrix: This is the result of multiplying the values of the joint level of severity – found in Phase 2 – by the values of the matrix of interrelationship and intensity – found in Phase 3. Each result of this new matrix is called ‘risk factor’ (RF). These results are shown in the section four of the antepenultimate figure of the paper ‘Establishment of the risk levels of user demands’, titled ‘Matrix of weighted demand risk’ and they reflect the breadth of the cases encountered in the investigation. The individual value of each risk factor, then, quantifies the likelihood of users filing a claim related to a failure, depending on the problem at hand.

3.6. Process of categorisation of the risk

Once the four phases of the first stage (method design) are completed, the second stage is initiated, with its single phase. In this regard, 5 categories of risk were established for user demands, according to the values obtained by the ‘risk factor’ (RF), such that the understanding and visualisation of the obtained results is facilitated. Likewise, the underlying technical knowledge is simplified, as is the associated decision-making. The above-mentioned categories were named: ‘Very Low’ (VL), ‘Low’ (L), ‘Intermediate’ (I), ‘High’ (H) and ‘Very High’ (VH).

3.7. Repair of the cause C01

Although a life cycle study [57] of this construction unit has not been included here, the impact of the CO2 emissions has been studied. This assessment is made only in relation to the most frequent cause: 'Incorrect lock/connection of the panes' (224 cases coded as C01). For this purpose, two estimative situations have been considered: fissures and horizontal openings existing at the meeting point of the partitions with the ceilings or floors -situation S1-; as well as the cracks and openings that are found at the vertical meeting point with other adjacent elements (walls, pillars, other partitions, etc.) -situation S2-. The repair of these cracks will also involve repairing the partition coatings [58].

For the calculation of CO2 emissions in both situations, the materials used in the repairs, the energy consumed by the equipment during the repairs, and the transportation of materials and waste were taken into account. CO2 emissions from Materials were determined for each material by multiplying the material density by the quantity of material and the CO2 emission parameters of the respective material. CO2 emissions due to Energy were determined for each equipment by multiplying the equipment's working hours by the equipment's power and the CO2 emission parameters of energy. CO2 emissions from Transportation were determined by multiplying the number of trips by the average distance and the CO2 emission parameters of the vehicle.

4. Results

4.1. Values according to the types of causes

The cluster analysis allowed to obtain the most mathematically appropriate associations, between the types of causes obtained. First, the optimal number of associations was evaluated. From the analysis of the WSS curve, of BSS/TSS and of s(i), it was found that the optimal number of associations was 4. This was due to the combination of the position of the elbow being around the number of 4 associations, as well as to the values obtained by the two parameters in comparison with other combinations. Namely, BSS/TSS obtained a value of 98.8% and s(i) obtained the following average values (Fig. 2): cluster 1 obtained a value of 0 (association with only one individual); cluster 2 obtained a value of 0.57; cluster 3 obtained a value of 0.58; and cluster 4 obtained a value of 0.84. Individually, by type of cause, the values of s(i) are as indicated in Table 2.

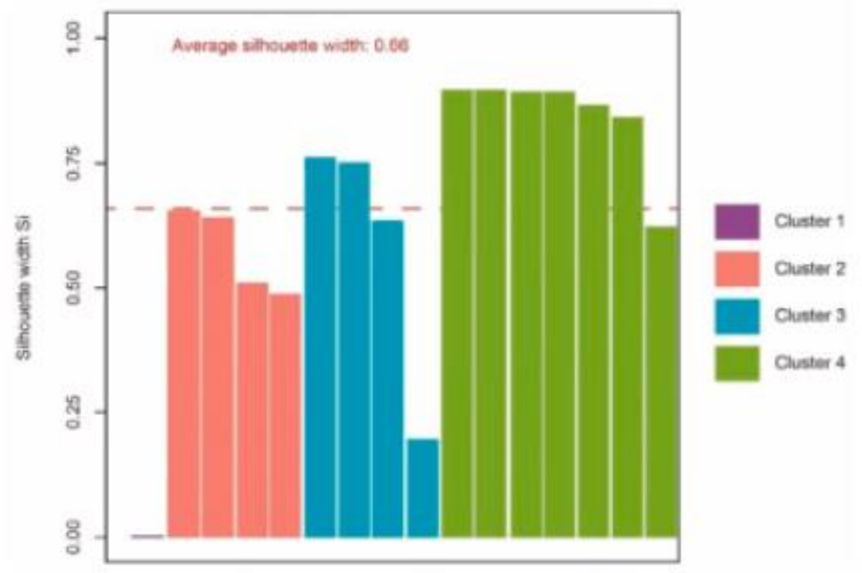


Fig. 2. Values of the silhouette index in each cluster group and individual values of s(i) by each type of cause.

Based on the values obtained (represented in Fig. 3), the causes of cluster 4 (with individual values less than 2%) have been described as ‘trivial causes’. The causes of cluster 3 (with individual values greater than the 2% and less than 7%) have been described as ‘secondary causes’. In turn, cluster 2 and cluster 1 join together the main causes behind the damages catalogued in this research. Given the significant preponderance of cluster 1, C01 has been described as a ‘critical cause’. The remaining causes (C05, C06, C07 and C02) were described as ‘primordial causes’. It should be pointed out that the causes of clusters 1 and 2 add up to nearly 75% of all cases (74.79%). In other words, around a third of causes (5 out of 16) concentrate a quarter of the causal origins in this research.

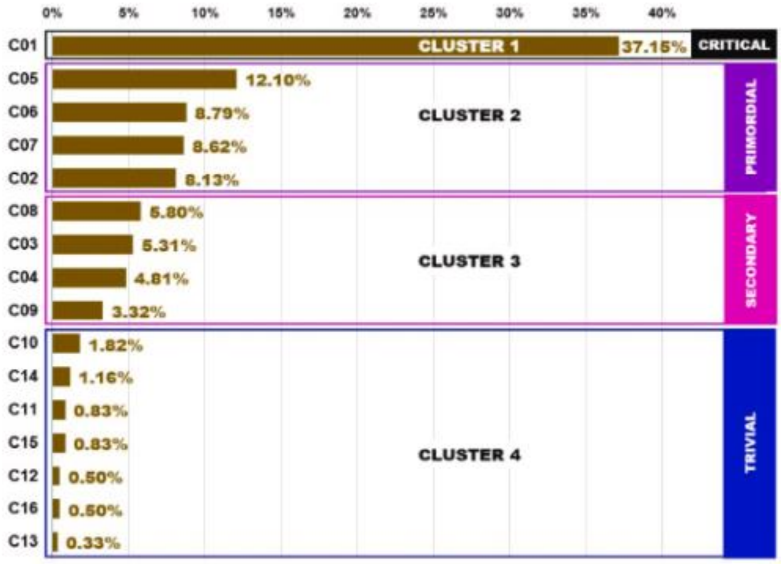


Fig. 3. Percentage of presence of each cause, as well as group and designation of each cluster obtained from the mathematical analysis.

4.2. Values according to the types of damages

The percentage value obtained by each one of the types of damages is unequal (Fig. 4). The first corresponds to around half the total (cluster A) and the second to nearly a quarter (cluster B). This implies that 7 out of 10 damages are concentrated in these two types of fissures, which highlights the fact that these damages (belonging to the Group D.AG-F) are clearly the ones that one should try to minimise during commissioning.

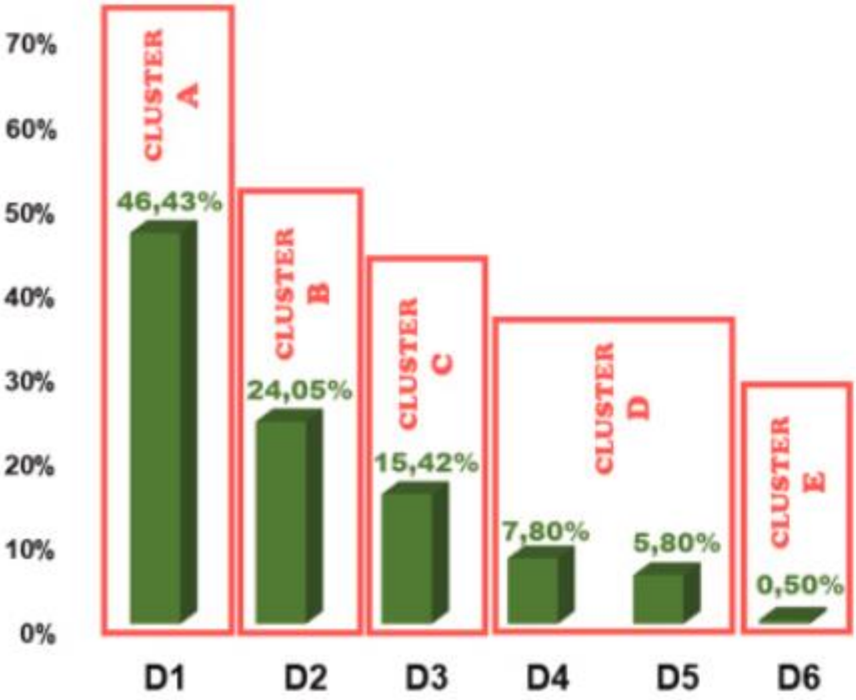


Fig. 4. Percentage value obtained by each one of the six types of existing damages.

Five different clusters have been obtained. The analytical procedure used to determine them is the same as that expressed previously for the causes.

4.3. Values according to the types of buildings

The values obtained by each type of building are: B1 = 402 cases, B2 = 184 cases and B3 = 17 cases. In other words, the first type (apartment blocks) concentrates 2/3 of all cases.

4.4. Values according to the technical affinity groups

Fig. 5 shows the values obtained according to the technical affinity groups of damages and of causes, it being noted that the more preponderant ones are D.AG-F and C.AG-I, respectively. Equally, in Table 3 shows the numerical interrelationship that exists with respect the affinity groups (causes and damages).

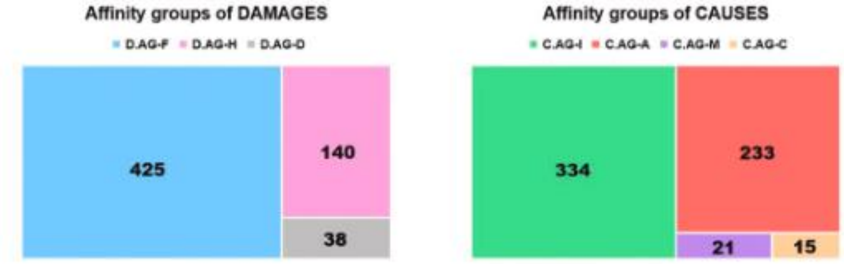


Fig. 5. Values obtained according to the technical affinity groups of damages and of causes.

4.5. Recurrence by types of buildings according to damage and cause

Table 4 shows a breakdown with the distribution of cases by technical affinity group and by type of building. The values in blue were subsequently used in the calculation of the risk of demand.

Table 4. of cases by type of building, technical affinity group of damages, and of causes.

Presence of each interrelationship			Technical affinity groups of causes				TOTAL
			C.AG-M	C.AG-C	C.AG-A	C.AG-I	
Types of buildings and technical affinity groups of damages	B1	D. AG-D	0,00 *(0.00)*	0,00 *(0.00)*	0,00 *(0.00)*	2,69 *(1.49)*	– (1.49)
		D. AG-H	0.00 *(0.00)*	40.00 *(1.00)*	34.33 *(13.27)*	0.00 *(0.00)*	– (14.27)
		D. AG-F	66.67 *(2.32)*	0.00 *(0.00)*	34.76 *(13.43)*	63.48 *(35.16)*	– (50.91)
		→ SUM	66.67 (2.32)	40.00 (1.00)	69.09 (26.70)	66.17 (36.65)	– (66.67)
	B2	D. AG-D	0.00 *(0.00)*	13.33 *(0.33)*	0.00 *(0.00)*	7.78 *(4.31)*	– (4.64)
		D. AG-H	0.00 *(0.00)*	33.33 *(0.83)*	17.60 *(6.80)*	0.00 *(0.00)*	– (7.63)
		D. AG-F	33.33 *(1.16)*	0.00 *(0.00)*	8.58 *(3.32)*	24.85 *(13.76)*	– (18.24)
		→ SUM	33.33 (1.16)	46.66 (1.16)	26.18 (10.12)	32.63 (18.07)	– (30.51)
	B3	D. AG-D	0.00 *(0.00)*	6.67 *(0.17)*	0.00 *(0.00)*	0.00 *(0.00)*	– (0.17)
		D. AG-H	0.00 *(0.00)*	6.67 *(0.17)*	3.01 *(1.16)*	0.00 *(0.00)*	– (1.33)
		D. AG-F	0.00 *(0.00)*	0.00 *(0.00)*	1.72 *(0.66)*	1.20 *(0.66)*	– (1.32)
		→ SUM	0.00 (0.00)	13.34 (0.34)	4.73 (1.82)	1.20 (0.66)	– (2.82)
	GL	D. AG-D	0.00 (0.00)	20.00 (0.50)	0.00 (0.00)	10.48 (5.80)	– (6.30)
		D. AG-H	0.00 (0.00)	80.00 (2.00)	54.93 (21.23)	0.00 (0.00)	– (23.23)
		D. AG-F	100 (3.48)	0.00 (0.00)	45.07 (17.41)	89.52 (49.58)	– (70.47)
		→ SUM	100 (3.48)	100 (2.50)	100 (38.64)	100 (55.38)	– (100)

Observation.

All numerical values are given in percentages, based on the number of cases that were determined.

The higher values are indicated with respect to the general computation of each group of causes, and the one parenthesis with regard to the total of the study. The values that are in blue and italics are carried over and used in Phase 3 (see Fig. 6).

Abbreviations.

B1: Type of building= Apartment blocks.

B2: Type of building= Houses.

B3: Type of building= Other buildings.

D.AG-D: Group of damages 'Diverse effects'.

D.AG-H: Group of damages 'Effect of Humidities'.

D.AG-F: Group of damages 'Effect of Fissures'.

C.AG-M: Group of causes of conditions pertaining to materials.

C.AG-C: Group of causes of conditions of contact between elements.

C.AG-A: Group of causes of conditions due to absences and deficiencies.

C.AG-I: Group of causes of conditions due to incorrect placement.

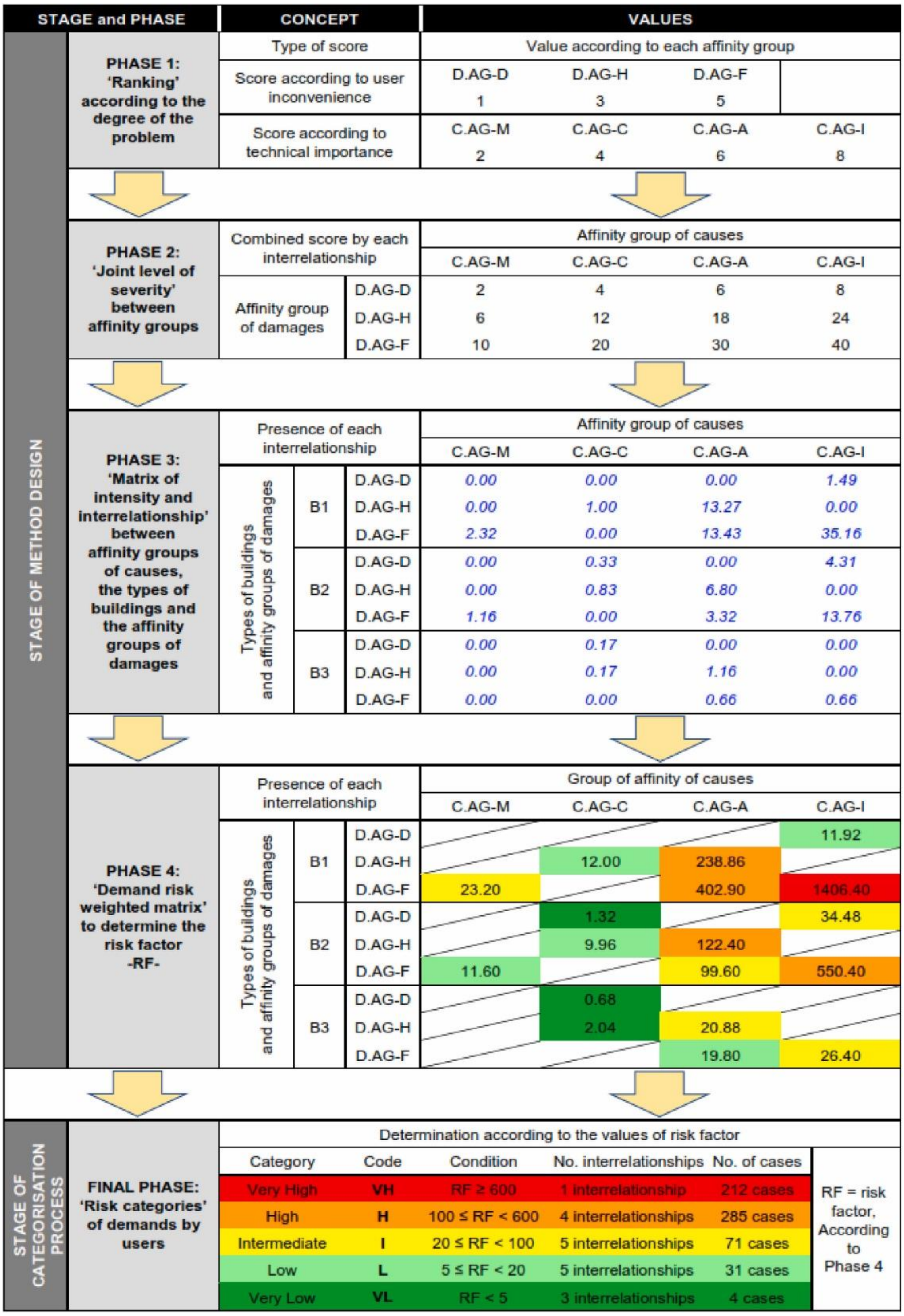
GL: Global.

4.6. Calculation of the risk of demands

With the results obtained through the process of categorisation of the risk, it can be noted that there is a large amplitude of values: the largest is 2068 times greater than the smallest. The cut-off values that constitute the limit between categories (according to the decision of the expert arbitrators), correspond to a risk factor of 5, 20, 100 and 600 (results greater than this last value have the highest effective risk of demand). The last section of Fig. 6 shows which have the highest number of cases.

4.7. Risk factor evaluation (RF values)

Below were considered the 18 values of risk factor resulting from Phase 4 (where the sum is 2,994.8) to study the proportions among them. When we order the values in decreasing order, we found that 27.8% of interrelationships (5 out of 18) accumulate 90.9% of all the values of risk factor (2721 out of 2994.8); therefore, a Pareto relationship of approximately ≈28–91 exists, as expressed in Fig. 7. In addition, ≈28% of interrelationships are included in the total of the values of risk factor related to the categories 'Very High' and 'High'.



STAGE and PHASE		CONCEPT	VALUES			
STAGE OF METHOD DESIGN	**PHASE 1: 'Ranking' according to the degree of the problem**	Type of score	Value according to each affinity group			
		Score according to user inconvenience	D.AG-D 1	D.AG-H 3	D.AG-F 5	
		Score according to technical importance	C.AG-M 2	C.AG-C 4	C.AG-A 6	C.AG-I 8

PHASE 2	Combined score by each interrelationship		Affinity group of causes			
			C.AG-M	C.AG-C	C.AG-A	C.AG-I
PHASE 2: 'Joint level of severity' between affinity groups	Affinity group of damages	D.AG-D	2	4	6	8
		D.AG-H	6	12	18	24
		D.AG-F	10	20	30	40

PHASE 3	Presence of each interrelationship			Affinity group of causes			
				C.AG-M	C.AG-C	C.AG-A	C.AG-I
PHASE 3: 'Matrix of intensity and interrelationship' between affinity groups of causes, the types of buildings and the affinity groups of damages	Types of buildings and affinity groups of damages	B1	D.AG-D	*0.00*	*0.00*	*0.00*	*1.49*
			D.AG-H	*0.00*	*1.00*	*13.27*	*0.00*
			D.AG-F	*2.32*	*0.00*	*13.43*	*35.16*
		B2	D.AG-D	*0.00*	*0.33*	*0.00*	*4.31*
			D.AG-H	*0.00*	*0.83*	*6.80*	*0.00*
			D.AG-F	*1.16*	*0.00*	*3.32*	*13.76*
		B3	D.AG-D	*0.00*	*0.17*	*0.00*	*0.00*
			D.AG-H	*0.00*	*0.17*	*1.16*	*0.00*
			D.AG-F	*0.00*	*0.00*	*0.66*	*0.66*

PHASE 4	Presence of each interrelationship			Group of affinity of causes			
				C.AG-M	C.AG-C	C.AG-A	C.AG-I
PHASE 4: 'Demand risk weighted matrix' to determine the risk factor -RF-	Types of buildings and affinity groups of damages	B1	D.AG-D				11.92
			D.AG-H		12.00	238.86	
			D.AG-F	23.20		402.90	1406.40
		B2	D.AG-D		1.32		34.48
			D.AG-H		9.96	122.40	
			D.AG-F	11.60		99.60	550.40
		B3	D.AG-D		0.68		
			D.AG-H		2.04	20.88	
			D.AG-F			19.80	26.40

STAGE OF CATEGORISATION PROCESS	Determination according to the values of risk factor					
	Category	Code	Condition	No. interrelationships	No. of cases	
FINAL PHASE: 'Risk categories' of demands by users	Very High	VH	RF ≥ 600	1 interrelationship	212 cases	RF = risk factor, According to Phase 4
	High	H	100 ≤ RF < 600	4 interrelationships	285 cases	
	Intermediate	I	20 ≤ RF < 100	5 interrelationships	71 cases	
	Low	L	5 ≤ RF < 20	5 interrelationships	31 cases	
	Very Low	VL	RF < 5	3 interrelationships	4 cases	

Fig. 6. Establishment of the risk levels of user demands.

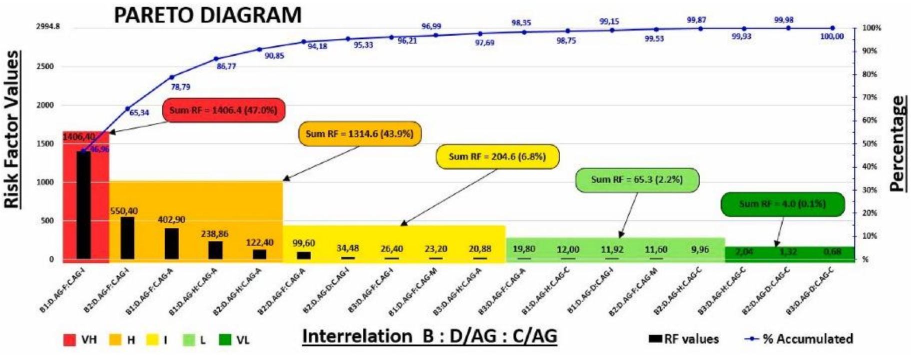


Fig. 7. Pareto relationship indicating the values and categories of risk factor, the codes of interrelationship among the types of buildings, the affinity groups of damages and causes, as well as the categories of demand risk.

This can be translated into the following technical interpretation of the 5 most important interrelationships:

1-Cases existing in apartment blocks with damages related to effects of fissures caused by incorrect conditions of placement.

2-Cases existing in houses with damages related to effects of fissures caused by incorrect conditions of placement.

3-Cases existing in apartment blocks with damages related to effects of fissures caused by conditions due to absences and deficiencies.

4-Cases existing in apartment blocks with damages related to effects of humidities caused by conditions due to absences and deficiencies.

5-Cases existing in houses with damages related to effects of humidities caused by conditions due to absences and deficiencies.

With this Pareto diagram it is clearly shown that if action is taken on the 5 top interrelationships (whether in the stage of design or in the phase of execution), litigation can be considerably reduced, as can the number of anomalies.

4.8. Damage-cause binomial pair

The focus on the individual correspondence between damages and causes does exist in some professional studies on anomalies, in the surrounding of rehabilitation interventions of any type of buildings in particular. However, that yields a knowledge which is reduced and ad hoc, about a specific case, not enabling the learning of lessons that might allow the expansion of the knowledge that forensic engineering has about failures occurring in partition walls in buildings. The authors of this paper believe that it is essential to have a unified perspective, broken down and quantified through epidemiological studies of large number of cases, such as those reviewed in this article. In this way, Fig. 8 deciphers the totality of the cases, yielding what is referred to as 'set of global damage-cause binomial pairs' of a given population. Out of the 22 binomial pairs found in this study, D1-C01 is highlighted.

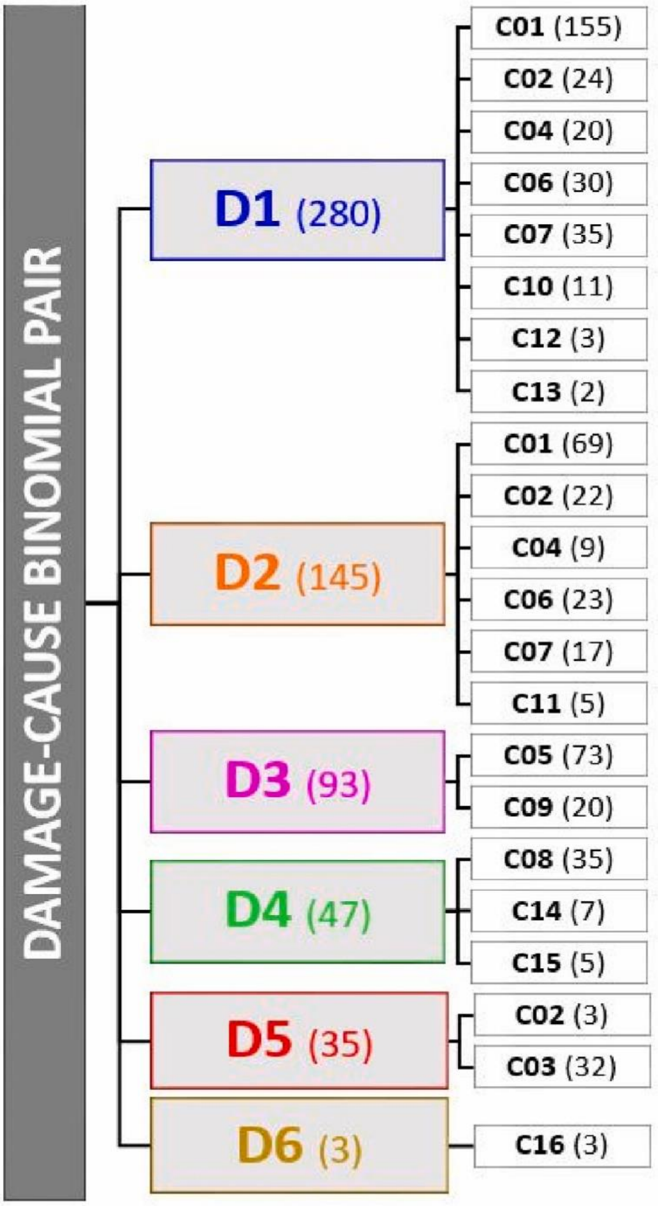


Fig. 8. Breakdown of all the damage-cause binomial pairs existing in the set studied (number of cases in parentheses).

From among the scientific literature reviewed for this research, no precedents were found in which there was an absolute breakdown, detailed and quantified on all the binomial pairs of the cases studied. Probably, the reason for the absence of such information is the significant difficulty to obtain large populations of real cases. As such, the authors consider that this paper offers a substantial contribution to the scientific knowledge in construction.

4.9. Calculation of CO2 emissions for situations S1 and S2 of C01

On this study, 224 cases of 'incorrect lock/connection of the panes' (code C01) were found – only cause considered critical–. The incorrect connection was found on the bottom and top of the wall pane, and on the left and right of the wall pane. To estimate the CO2 emissions associated with repairing these fissures, we considered two situations (Fig. 9).

Fig. 9. Central perspective of a wall with indication of repair zones for situations 1 and 2 of case C01.

In situation 1 (S1), we assumed that the repair would consist of opening a groove along the fissure on the top and bottom of the partition wall with a depth of 1.5 cm, include a fiberglass mesh and replacing the plaster. In situation 2 (S2), we assumed that the repair would involve installing metal connectors. We considered that 1.2 connectors of 6 mm diameter and 30 cm long are required per meter of wall height. We conducted calculations to determine the CO2 emissions linked to the materials, energy usage and transportation required for each situation, as described in Table 5.

Table 5. CO2 emission parameters of materials, energy usage and transport.

Items	Concept	Unit	Emissions parameters	Source
Materials	Gypsum	kg/kg	0.13	ICE 2011 [59]
	Mortar (cement 1: sand 3)	kg/kg	0.18	ICE 2019 [60]
	Steel	kg/kg	1.99	ICE 2019 [60]
	Fiberglass mesh	kg/kg	3.31	ICE 2011 [59]
Energy	Electricity	kg/kWh	0.99	ICE 2011 [59]

Transport	Small truck	kg/t.km	0.089	Sustiain. Report 2009 [61]

For the 224 cases the CO2 emissions associated with situation 1 are indicated in Fig. 10, and for situation 2 are indicated in Fig. 11.

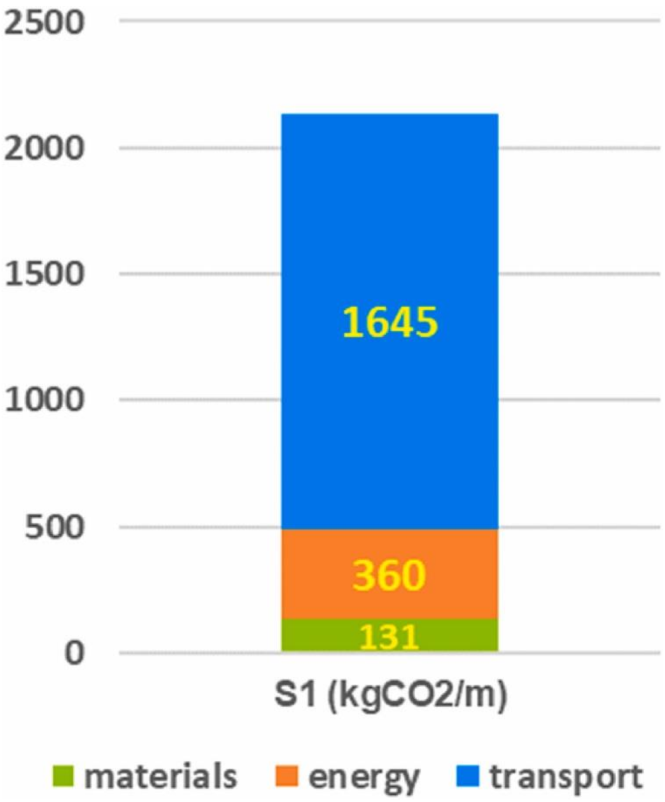


Fig. 10. CO2 emissions for S1.

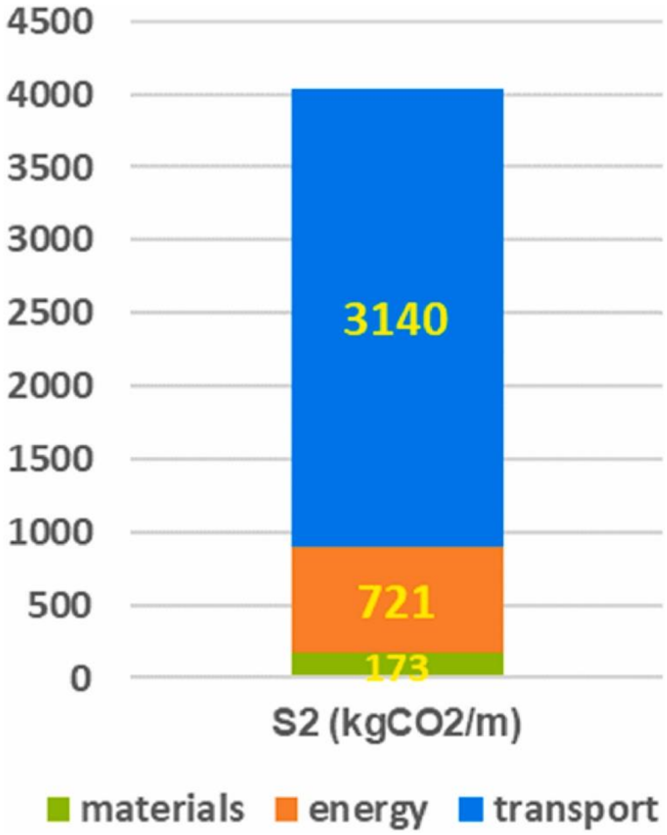


Fig. 11. CO2 emissions for S2.

These findings suggest that while the use of metal connectors may result in higher emissions than the traditional repair method, it may be a more effective long-term solution to prevent fissures from reoccurring.

As mentioned by Ke En et al. [44], the determination process of CO2 emissions involves a massive amount of information. In our study, we have observed that the repair of fissures in masonry walls can have a significant environmental impact in terms of CO2 emissions, with transportation contributing the most to the overall emissions. Our results suggest that the use of metal connectors may be a more sustainable solution, although further study is indispensable to fully assess the environmental impact of different repair methods. These findings show the relevance of including the environmental impact of construction practices and the need for more sustainable approaches to building maintenance and repair.

5. Discussion

5.1. Regarding the nature of the data used

As deduced from the information provided in the previous sections, one of the main achievements and innovations of this research is closely related to its nature (accessing data for which obtaining special permission for consultation is extremely difficult: judicial records, as well as reading forensic reports on the construction failures contained in them). In addition to this, it is highly unique to have been able to access the entirety of these records (both in terms of national scope and the number of cases). As a complement, the substantial number of records (over 600) and the fact that the verified constructions had no interrelation among them lend robustness to the values of the obtained results and provide the entire research with scientific independence, free from biases.

As a summary of the large amount of concepts addressed in the research, Table 6 describes the volume of data used.

Table 6. Volume of research data.

Concepts	**Value**
Number of cases	603
Number of years	10
Types of damages	6
Types of causes	16
Types of buildings	3
Damage clusters	5
Cause clusters	4
Affinity groups of damages	3
Affinity groups of causes	4
Number of scores in phase 1	7
Number of theoretical interrelations	36
Number of effective interrelations	18
Total risk categories	5
Number of codes in VH category	1
Number of cases in VH category	212
Number of codes in H category	4
Number of cases in H category	285
Number of codes in I category	5
Number of cases in I category	74
Number of codes in L category	5
Number of cases in L category	31
Number of codes in VL category	3
Number of cases in VL category	4
Number of damage-cause binomial pairs	22

5.2. About cluster analysis groupings

In relation to the causes, it is interesting that Cluster 1 consists of a single type of damage, which is related to repetitive manual operation in the process of raising the partition wall (C01). The practice of incentivizing workers to earn more money based on the number of square meters they complete is undoubtedly one of the factors that can influence this, as they are paid the same amount regardless of the quality of their work. Cluster 2 and 3 are related to aspects where the knowledge and quality of workmanship of the bricklayers are crucial. However, Cluster 4, which involves concepts that involve other factors such as other individuals and materials, has the lowest number of cases.

Regarding the damages, it is observed that Cluster A and B are related to the two types of fissures, which are the most common issues in partitions (also more related to the intervention of bricklayers). Meanwhile, Cluster C and D concentrate on cases related to types of moisture problems.

5.3. Comments on other research studies

In the literature, Diaz et al. [16] presents several cases of deterioration in brick walls façades that were between concrete slabs in Spain, analyzing 22 buildings in various Spanish locations. Although it does not provide solutions or analyze the environmental impact of these repairs, it emphasizes the need to observe the buildings behavior. The authors identify the causes that provoked the damages and relate them to the constructive solutions. These aspects are directly related to the study conducted here, emphasizing the need for better construction practices.

5.4. Some considerations on sustainability

The path to sustainability involves all stakeholders who participate in it. Quantifying sustainability is very challenging due to the lack of up-to-date data. Machine learning and big data, combined with Building Information Modeling (BIM), could potentially help obtain more accurate data on constructions in the near future. It is necessary for the different participants in the process to share their information and for that information to be examined in order to enhance the construction process.

5.5. Limitations and recommendations for future research

This research study is conducted on newly constructed buildings that are within a timeframe close to when their construction was completed. While this is not necessarily a limitation in itself but rather a specific scope of investigation, it is important to be aware of it to understand its nature properly.

For future research, other studies can be conducted on different types of partitions (constructed with wood, plasterboard, etc.) to compare the results. It may also be of interest to explore the possibility of understanding the influence (or lack thereof) that the location of the buildings in question could have, particularly in more unstable areas (such as areas with poor soil quality, regions with varying degrees of seismic activity, etc.). However, for the latter, the cases would need to be segmented based on technical or normative parameters and then associated with specific geographic areas, which is not currently available information from the judicial records.

5.6. Photographic complement of some damages

In order to provide readers with visual representation of some of the studied damages, the following 4 photographs are included (see Fig. 12).


Fissures originating in the construction (corner of a partition)

Humidity by condensation (repairs in a living room)

Rising damp at the bottom of a partition wall

Existence of spots or dirt on the inside face of a bedroom

Images by Manuel J. Carretero-Ayuso

Fig. 12. Photographic examples of some damages in partition walls.

6. Conclusions

Research done on the totality of the cases occurring in a country are rare, and it is especially rare that the cases derive from judicial records and that the subsequent analytical process is based on non-appealable court rulings, because it is tremendously complicated that the national Administration to allow research on them. A review of international literature did not find any comparable precedent for ceramic brick walls (which constitutes a significant novelty in the field of scientific knowledge and forensic engineering).

The procedural framework used is formed by obtaining the type and number of construction failures from said sentences, by the participation of a series of expert arbitrators, by the creation of a scoring system for the failures (divided into 5 phases) as well as by the ranking of cases according to categories of demand risk.

It was found that the most common type of damage is ‘fissures originating in the construction’ (D1 = 46.43%), and the most common type of cause is ‘incorrect lock/connection of the panes (C01 = 37.15%).

Lastly, one should highlight the importance of a collective reflection on the significant costs of re-work resulting from improper execution, as well as on the impact that it may have in the long run on the increase in maintenance operations during buildings' service life. One step to combat this impact would be to include in national regulations the most problematic points of the main construction units. This would require the prior creation of a database compiling those problematic points – which could be meaningfully accomplished from actual cases of demands, as presented in this study.

Given the prevalence of the construction unit in question, the authors understand that the values specified in this research could be similar to those that could be obtained in other nations in the region, with any adaptations that may be necessary.

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