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Calculation of the Risk of Lawsuits over Construction Flaws in Flat Roofs

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Abstract: In order to achieve sustainability objectives in the use of a building, its elements' operating problems should be minimized. From this premise, a total of 497 cases related to construction flaws in flat roofs were analyzed in this research. A matrix was developed indicating the risk of lawsuits by owners according to the degree of nuisance resulting from the construction flaws studied, their technical importance, and the type of pathological origin. Based on these factors, it is possible to predict a greater or lesser probability of an owner filing a lawsuit—risk factor (F). A wide range was found for this probability, with the largest value being 865 times greater than the smallest value. The value of F was divided into 5 categories to classify the diverse results obtained and determine the number of cases and interrelations ascribed to each category. Additionally, the level of presence of said cases was calculated through the analysis of 3 different demographic aspects, it being noted that a greater purchasing power and a higher concentration of urban population lead to more stringent requirements and, subsequently, to a greater number of lawsuits. With all these results, building quality can be improved while resulting in greater constructive-financial sustainability and in a reduction of the economic resources required of society (fewer lawsuits and associated human resources).

Keywords: construction pathologies; roofs; defects; risk; sustainability

1. Introduction

Flat roofs can be used for a number of functions, according to their different typologies [1], being adaptable to building's neighbors' needs. They can be used in new strategies for water management in urban contexts, improving the sustainability of cities. In this way, industrial phytodepuration systems can be incorporated in large roof surfaces, allowing for a reduction in both the consumption of drinking water and the volume of water poured into sanitation networks. The results of a study on this subject demonstrate that it is possible to achieve savings of 59% in water consumption [2]. Also related to sustainability, Guzmán-Sánchez et al. [3] carried out an analysis of three different climate scenarios according to a list of indicators for the sustainable development of flat roofs, while Shin and Kim [4] perform a benefit and cost analysis of green roofs.

While not going into the analysis of these new areas of focus with regard to urban use, it should be noted that building roofs are currently one of the construction zones which most significantly bear the effects of the passage of time: the lack of periodic control and the action of environmental agents increase the probability of their deterioration [5]. As such, building roofs are among those construction elements the preservation of whose materials is of the highest importance. In this regard, buildings without proper maintenance [6] usually manifest early on the appearance of certain imperfections, for which reason they are among the first areas to require renovations or replacement of elements in order to prevent humidity and infiltrations [7].

For owners as well as owners of buildings, the existence of a quality management system during the design stage of waterproofing systems would ensure higher levels of comfort in buildings, as well as higher efficiency throughout the service life [8]. According to Garcez et al. [9] design defects in roofs are a constant characteristic in many countries, and only an improvement of the quality of design planning can lead to a significant reduction in execution defects and to a maximization of the service life of these elements. As Conceição et al. [10] consider that it is necessary to increase both the effectiveness and objectivity of the actions required for the repair of construction flaws, they accordingly centered their research of 105 flat roofs on the inspection, diagnosis and rehabilitation of this construction element.

For the staff participating in design and execution (designers, construction managers, construction firms and manufacturers/suppliers), waterproofing should be analyzed in depth and in detail, according to the characteristics of the environment in which the construction is located. This would effectively help to ensure that the waterproofing system functions correctly [8].

As mentioned, roofs are often one of the most vulnerable construction zones, given their characteristics and exposure to atmospheric agents (wind, snow, solar radiation and variable and extreme temperatures) [11]. This reality manifests itself in places as far apart as Spain and Australia, which some might presume to have very different social/construction characteristics. A study in the Australian state of Victoria [12] indicated that, in that country, enormous resources are spent to reactively address endemic construction flaws: roofs were found to be the second zone with the most construction flaws.

The high vulnerability of flat roofs is recognized in many other countries, such as in Switzerland. In the Canton of Ticino, a pilot program was run in the early years of the 21st century to establish a maintenance plan for 42 public buildings. Once concluded, flat roofs (numbering 50 roofs assessed) were the construction zone with the highest number of repair and conservation initiatives [13]. As stated, then, maintenance is of essential importance in flat roofs so as to prevent flaws in waterproofing systems from leading to important and costly damages, imperfections and infiltrations [14].

With a focus on problems caused also by flat roofs, a recent study in Malaysia examined 23 higher education buildings, identifying therein different types of imperfections [15]. In some cases, construction flaws were related to the slope of roof plans, and to the tail-end with the parapets [16]. In that paper, it is suggested that a modification in how designs are produced could have decisively led to a different outcome with regard to quality. Results from other countries might be worse still, as Garcez et al. [9] have observed that, in many countries, the execution of flat roofs is usually not based on designs which include specific construction details or views with sufficient definition.

With regard to other aspects researched about flat roofs, a series of recent studies has focused on the analysis of the materials themselves, or of the application procedures [17]. This is the case of studies examining the mechanical behavior between waterproofing membranes [18], the dimensional stability [19,20], the influence of wind suction [21], joints submitted to artificial weather [22], flaw analysis [23] or procedures to incorporate parameters in water tightness tests [24,25]. Another area that recent research has focused on pertains to green roofs, evaluating, for example, stormwater runoff retention [26], energy performance, or impact on ozone levels [27].

In turn, overlapping joints between membranes are one of the points where many problems are found [19]. Indeed, the way they are executed is highly associated with the existence of construction flaws, with dimensional changes at times leading to the disappearance of the overlap (it is for this reason that it is beneficial to include fiberglass mesh in the membrane, as it results in dimensional stability). Different types of bituminous membranes are self-protected by mineral granules; these granules constitute a barrier against the deterioration caused by ultraviolet radiation [28]. As such, one way of assessing the long-term performance of waterproofing is to test the adherence of the self-protection layer to the membrane itself.

Waterproofing layers of roof systems have traditionally been bituminous [29] and, despite the existence for decades of other waterproofing systems, single-layer bituminous systems represent the majority of waterproofing systems installed around the world [30]. Nevertheless, liquid-applied roof waterproofing systems (LARWS) have recently gained prominence; Feiteira et al. [31] studied their mechanical performance and deformability.

In a completely different field of knowledge can be found those studies in which certain demographic factors (human population, mortality, fertility, etc.) are included. These areas of focus tend to be more common in the social, law, or health fields than in engineering. In the latter field, the research published in the last few months has examined socio-demographic trends for electric vehicles [32], and the possibility of collisions in freeways [33]; nevertheless, no research was found to establish a percentage relation between construction flaws in buildings and population weight. This research intends to explore the correlations existing in this latter aspect.

In light of the above, the main limitation of the state of the art on flat roofs would lie in the fact that most research on flaws in building roofs has been based on surveys or on observation processes (normally with small sample sizes) which, unlike actual lawsuits, may lead to bias issues. The only precaution associated to the use of lawsuits is that these may also include other aspects outside of the technical field (professional incompetency, fraud, breaches of contract, etc.). Such circumstances are not taken into account in this research, for which reason the only lawsuits considered were those that included an expert technical report, with the complaint stemming from construction flaws (infiltrations, fissures, etc.). Within the international bibliography consulted, no precedents were found to resort to lawsuits by owners as their data source, for which reason this new perspective could constitute a useful contribution to the knowledge of forensic engineering.

One way of evaluating, and subsequently classifying said construction flaws is to incorporate methods that allow taking into account the value of a series of complementary aspects. In industry and in the economy many tactical and strategic decisions are made [34] by weighing parameters that influence an investment (or taking a position in the market) without a prior universal establishment of their weight/importance [35]. The weighted factors method allows taking decisions [36] from criteria such as utility, customer perceptions or sociological characteristics (for example) for which one should establish a percentage of participation in the final decision. In our scope, the criteria to be implemented may be defined by a group of qualified senior technicians [37] in place of the manager, financial director or board of administrators of a company.

This paper, then, has several objectives:

- Firstly, to outline those construction flaws which are most common in flat roofs, based on lawsuits filed by owners in Spain, as well as indicate their types of pathology origins, classified by different building typologies;
- Secondly, to develop a tool for the determination of probability and risk of lawsuits based on the creation of a weighted risk matrix and the establishment of categories according to the 'risk factor';
- Thirdly, to determine the percentage of distribution of the construction flaws analyzed and their greater or lesser presence in population centers, according to the number of inhabitants and the gross domestic product per capita.

The attainment of the three indicated objectives is intended to help achieve a product (flat roofs) with fewer problems. This stands as a general "super-objective", reached through the attainment of the three partial objectives described above. The goal of a sustainable construction process should be a building in optimum condition, so that construction flaws may be reduced in future work carried out on the building. In order to achieve this goal, it would be interesting to produce a governmental public catalogue containing the construction points with the greatest number of flaws, based on actual/judicial cases, as presented herein. Equally, the knowledge of construction anomalies should be increased in architecture and engineering students, so as to equip them to identify those critical points in roofs, in order to avoid repeating problems in the future (both in the design and construction phases). Finally, and based on the most frequent flaws, construction codes could be modified to include specific construction details on the most secure way to address critical points (especially: Connections with drains, the minimum height that waterproofing should reach from the lower part of the roof's perimeter walls, and the minimum distance between the level of the roof's finishing and the lower sills of frames of doors opening out to terraces).

2. Methodology

2.1. Origin of the Data, Scope and Procedure

This paper intends to describe the data collection, classification, analysis and results obtained with regard to a specific zone: flat roofs of buildings. Its documental foundation is the data extracted from the records of civil responsibility insurance policies of technical architects and building surveyors in all of Spain [38]—an insurance company dedicated to civil and construction insurance. All such records meet the condition of proceeding from lawsuits filed between 2011 and 2012 [39] which in the subsequent years came to receive final and unappealable rulings from the courts [40]), following several years of litigation until the final conclusion was arrived at. In general, this technical documentation is structured according to what the regulation [41] specifies for reports on anomalies (background, data collection, inspection carried out, analysis, etc.).

When the owners of building experience certain construction problems, and these are not resolved within the warranty period, they often resort to the judicial route. Once this process is initiated, independent forensic building experts are charged with drafting reports describing the existence of the construction flaws claimed by said owners. These reports, paid for by the insurance companies of the respective technicians, constitute the sources of the data used.

Once the trial is initiated, the existence of said construction flaws, and their nature, extension and type are examined based on the technical-forensic reports presented. Once the judge rules on the matter, each of the litigant parties can appeal to a higher court, if they so wish. In that case, the lawsuit is re-opened until such time as the legal proceedings definitively conclude (whether in regional high courts or in the country's Supreme Court). This lengthy technical, administrative and judicial course is what allows to validate the data sources used and the reported findings, given that the defense or prosecution arguments presented throughout the case allow to demonstrate the veracity of the construction flaws object of lawsuits and of the causes of their origins.

In order to carry out this research, it was necessary to request permission to access all of the technical-judicial records mentioned (those with a final ruling). Subsequently, a detailed reading of each was carried out (each record contained hundreds of pages containing administrative, bureaucratic, technical, judicial and personal data, among others). Following an intense work of extraction, sorting and handling of the information, the 3 types of 'descriptors' on which this paper is based were determined—as explained below.

A significant quantity of data was handled, it having been necessary to standardize (classification by descriptors, use of the same terminology . . .) it for loading into a computer program. Following the corresponding reading and verification, a total of 497 cases related to building roofs could be extracted, corresponding to the totality of cases occurring in Spain during the above-mentioned time period. For this study, the methodological bases of the regulation [42], related to the actions pertaining to the assessment, identification and appraisement of construction flaws, were regarded.

No precedents were found of authors from other countries using this type of data source for the observation of problems in flat roofs, or of the data being used in published research papers. Furthermore, it should be taken into account that the results contained herein make a specific contribution to this field of scientific knowledge: they correspond to 100% of the time period mentioned above, for which reason it is not a partial sample (there is not, therefore, a possibility of errors or deviations). As such, the period of time between the moment the lawsuit was first filed and the time the information was fully read and analyzed was of several years.

2.2. First Phase of the Research

The three descriptors studied in this research are:

- Descriptor 1: 'Construction flaws'. According to the lawsuits filed by the owners, they correspond to: 'Condensations' (CF1), 'Fissures' (CF2), 'Humidity' (CF3) and 'Infiltrations' (CF4).
- Descriptor 2: 'Pathology origin' of the construction flaws. Categorized into two types:
    - 'Properties and characteristics of materials' (PCM): those related to the material itself, its format or intrinsic characteristics;
    - 'Conditions of placement and application' (CPA): those related to the prescriptions or omissions of the design, or to the indications and decisions made during the execution stage.
- Descriptor 3: 'Building typology'. The buildings studied were classified into: 'Apartment blocks' (T-A), 'Detached houses' (T-B), 'Semi-detached houses' (T-C).

The various situations and specific construction problems leading to construction flaws of the cases studied in this research were studied and categorized, as shown below:

Condensations (CF1). *Physical phenomenon through which environmental humidity liquefies when in contact with a cold wall*; cases were found in areas with insufficient thickness of the insulating material, lack of continuity in the insulating layer, lack of insulation on the roof.

Fissures (CF2). *Rupture of a construction element following a mechanical or thermal action, or as a consequence of a discontinuity*; cases were found in: fracture of the brick veneers of the corners of the roof slab, fissures of the baseboard of the roof floor, openings in the surface of the finishing, fissures in the coatings of the surrounding perimeter walls, lack of an elastic element between the edges of the roof plan and the inner face of the parapets, fissures/degradation of the layer exposed to the weather without surface protection, fractures due to low quality materials, stress and fatigue of materials with inadequate characteristics for their function, lack of expansion joints in the roof, lack of movement joints of the floor, fissures/detachment of the cement render of the parapets, fractures in the masonry elements of the parapets, insufficient concrete cover to reinforcement in the case of parapets made of reinforced concrete, dimensional contractions and expansions.

Humidity (CF3). *Effect of water on the finishing surfaces of certain materials due to loss of water tightness*; cases were found in: zones with poor adherence in the tail-ends of the waterproofing with the perimeter walls, deficient connections between drain flanges and standpipes, garden containers with poor water tightness, poorly finished construction joints, punching of the layer due to plant roots, existence of pores in the waterproofing layer, placement of drains in places which are above the lowest level of the roof, poorly resolved tail-ends with walls, lack of reinforcement layer in singularities, poor placement of some layers of the construction system, poor functioning of drain nozzles, insufficient slope of the slabs, insufficient overlap between layers, deteriorated sealing.

Infiltrations (CF4). Entry and/or presence of a significant amount of water in weak points of a construction element, leading to the dripping/visible loss of this liquid; cases were found in: pipes going across the layer leading to lack of continuity of the waterproofing and—as a result—the loss of water tightness, entry of water around the chimney, excess tightness in the vertical tail-end over the parapets, causing them to come loose, lack of waterproofing layer, placement of drain in a material which is incompatible with the waterproofing system, insufficient tail-end distance between the layer and the drain, absence of drains, water overflow, fracture of the layer, incorrectly designed expansion joints, detachment of the clamps holding the system around the anchorages fixed to the slab, perforation of the layer by mechanical actions, insufficient height of the sills of the doors accessing the roof, infiltrations through ventilation grids connected to openings over the roofs, losses of water next to installation sleeves, insufficient evacuation capacity of the available drains, deficient placement of gutters, obstructed drains, replacement of certain sections of the layer by a waterproofing paint, etc.

2.3. Second Phase of the Research

In a second phase of the research, 5 procedural stages were followed in order to evaluate and quantify the risk of filing of lawsuits. The first such stage involved consulting a group of 8 qualified senior technicians to carry out an 'interjudge validation', as per the Delphi technique and the UNE-EN-31010 regulation [43]. Individuals with a minimum of 20 years of work experience, and direct contact with the diagnosis and treatment of building construction flaws were considered. It was sought that the selected individuals would have diverse trajectories in order to provide a complete and multi-focal perspective (specialists of civil insurance companies, university professors, judicial experts, managers in companies with quality control laboratories, etc.). For construction flaws, the score is based on the degree of nuisance or perception of dissatisfaction by owners due to those flaws; the group of qualified senior technicians decided that these scores should be in odd numbers: 1, 3, 5, or 7. For the pathology origin, the scoring is carried out according to the degree of technical or construction importance which said origin represents; the group of qualified senior technicians decided that this score should be even: 2 or 4 points.

The description and procedure used in each of the 5 stages of phase 2 of the research is given below:

- **Stage 1**—Scoring by the degree of the problem represented by the type of construction flaw (CFx; first descriptor) and its pathology origin (CPA or PCM; second descriptor).

Stage 1A—The concept of 'possibility of occurrence' of a flaw or defect was extracted from the Spanish regulation UNE-60812 [44], to assign to the first and second descriptors of this study. It should be pointed out that the aforementioned regulation recognized within it that there is no univocal and universal definition to assign a 'possibility of occurrence'. It being necessary for those individuals carrying out the analysis (in this case, the qualified senior technicians that were consulted) to define and accept a common framework of action for each case, according to the specific discipline and sector it will be applied to *(for this situation: building construction > roofs > existence of construction flaws > construction risk of appearance of flaws > evaluation of risk from the perspective of lawsuits*). In this way, the *degree of nuisance or perception of dissatisfaction by owners due to the existence in their buildings of different types of construction flaws* was assigned individually by each of these qualified senior technicians. This was done as per their professional experience and considerations, according to the characteristics of said construction flaws and the problems of use or habitability, making owners more or less inclined to file a lawsuits in the courts (this process was carried out without them being informed of the results of the data collection).

Stage 1B—The qualification of the classes included in said regulation to define the possibility of occurrence (singular, occasional, probable and frequent) were associated to the scoring indicated above: 1, 3, 5, and 7 points, respectively (association of a conceptual scale to a numerical scale). In this regard, the procedure used was based on the 'weighted factors method', with the necessary adaptations. Thus, the intervening concepts being scored are the type of flaw (CF2, CF1, CF3 and CF4) and the scoring scale to be applied (1, 3, 5 and 7, respectively) is the same for all (applied in bijective manner). The process of value attribution in the original method is done by the management of a company or entity and, in this case, by several qualified senior technicians.

Stage 1C—With regard to the prior consideration, this procedure was analogously carried out to the second descriptor (pathology origin).

- **Stage 2**—Level of joint severity, defined as the numerical combination of the scores defined in Stage 1. The second part of table of Section 3.4 (Determination of Categories of Lawsuit Risk) shows the results, obtained by multiplying each type of pathology origin by each type of construction flaw.
- **Stage 3**—Each of the 24 possible combinations, resulting from the interrelation of the 4 types of construction flaws, the 2 types of pathology origins, and the 3 types of building typologies, was quantified. According to each interrelation's level of presence, an 'interrelation and intensity matrix' was defined, from which are obtained the percentage values of table of Section 3.2

(the results are shown in the third part of table of Section 3.4 (Determination of Categories of Lawsuit Risk)).

- **Stage 4**—A weighted risk matrix is created for lawsuits, resulting from multiplying the level of joint severity (determined in Stage 2) by the 'interrelation and intensity matrix' (determined in Stage 3). Each value of that matrix is named 'risk factor' (F). The results are expressed in the fourth part of table of Section 3.4 (Determination of Categories of Lawsuit Risk) and show how extensive and intense the cases found in this research can be. In this way, F numerically quantifies the possibility that an owner files a lawsuit about a construction flaw, according to the specific problem in question.
- **Stage 5**—Five risk categories for lawsuits by owners are created, according to the values obtained by F in the previous stage, as there is a wide range of results, in which the largest value is 864.5 times greater than the smallest value. With this categorization, the visualization and understanding of the results is facilitated.

2.4. Third Phase of the Research

In addition, a third phase of the research intended to ascertain the influence that certain external aspects can have in the studied cases. In this regard, a series of official demographic data was resorted to [45,46] and correlated with the number of construction flaws being considered by this research. For their better analysis and control, the demographic data was segmented into 4 classes (Table 1). Accordingly, we proceed to consider population (number of inhabitants), the number of houses and the gross domestic product per capita of the geographic area in which each lawsuit originates. These areas are provinces and can be considered analogous to the counties of some Anglo-Saxon countries.

Table 1. Name and distribution of classes according to demographic aspects.

Code	Concept	Classes			
P	Population (number of inhabitants)	P1 <500,000	P2 ≥500,000 and <1,000,000	P3 ≥1,000,000 and <3,000,000	P4 ≥3,000,000
H	Number of houses	H1 <200,000	H2 ≥200,000 and <400,000	H3 ≥400,000 and <1,000,000	H4 ≥1,000,000
G	Gross domestic product per capita	G1 <17,000	G2 ≥17,000 and <20,000	G3 ≥20,000 and <25,000	G4 ≥25,000

3. Results

The three following sub-chapters specify the results obtained for each of the three descriptors, as well as the explanation of the analysis procedure to quantify the 'risk of filing lawsuits in court', of which there is no prior set concept in the current scientific literature. The results of phase 1 of the research are shown in Sections 3.1–3.3. Phase 2 of the research is described in Section 3.4 of this paper (and contains 5 stages). Finally, phase 3 of the research is described in Section 3.5.

3.1. Cases by Type of Construction Flaw

The distribution of construction flaws present in the flat roofs analyzed is presented in Figure 1. As shown, the highest value is obtained by 'Infiltrations' (CF4 = 45%; 223 cases), followed by 'Humidity' (CF3 = 38%; 191 cases).

The types of construction flaws were grouped into two sets, according to affinity. In this manner, Set W was established, grouping the types of construction flaws related to the existence of water, and Set C was established, grouping the types of flaws related to cracks. The resulting values are expressed in Figure 2, taking into account that Set W = CF1 + CF3 + CF4 and that Set C = CF2. As can be seen, the most numerous set is W with 434 cases (87%), while C includes only 63 cases (13%). As such, of all layers of flat roofs (formation of slopes, waterproofing, insulation, separating filters, cement mortar layers, etc.), the waterproofing layer is usually the most critical. This causes their problems to lead to different types of humidity and infiltration—in a very high percentage.

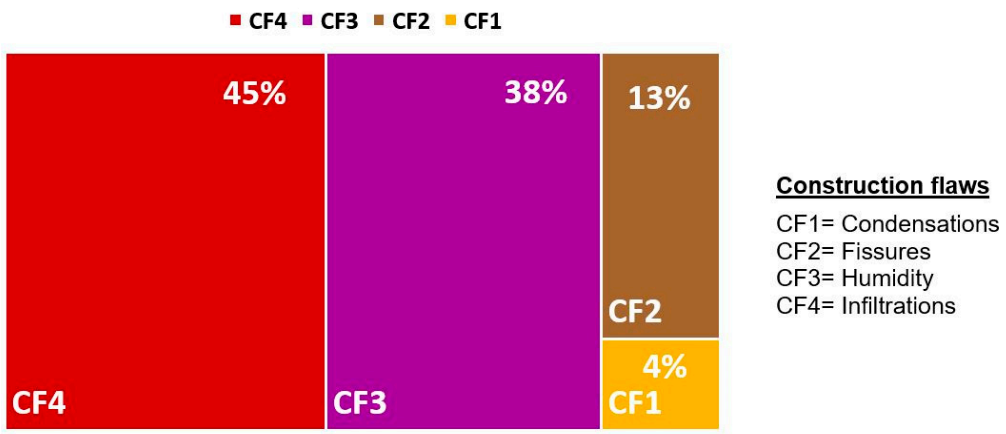

Figure 1. Percentage of cases by type of construction flaw.

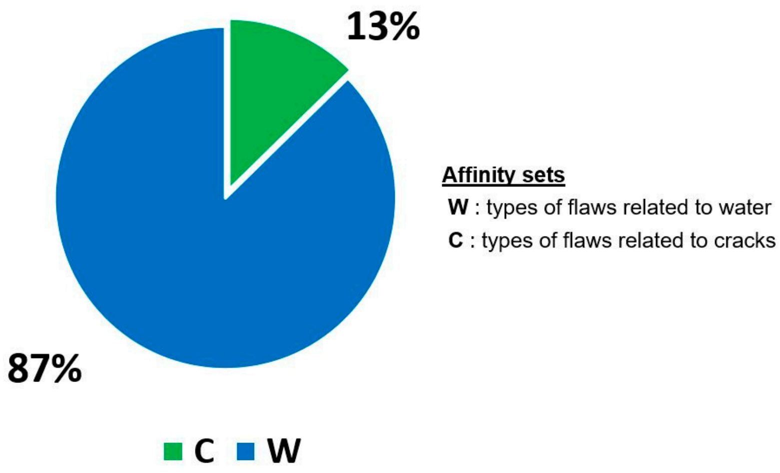

Figure 2. Percentage of cases by affinity sets.

3.2. Cases by Building Typology

As mentioned above, the typology of the building in which each construction flaw appeared was noted during the data collection process. The resulting values are presented in Figure 3, showing that approximately 62% of instances take place in apartment blocks (T-A). In turn, detached houses (T-B) and semi-detached houses (T-C) are nearly equal.

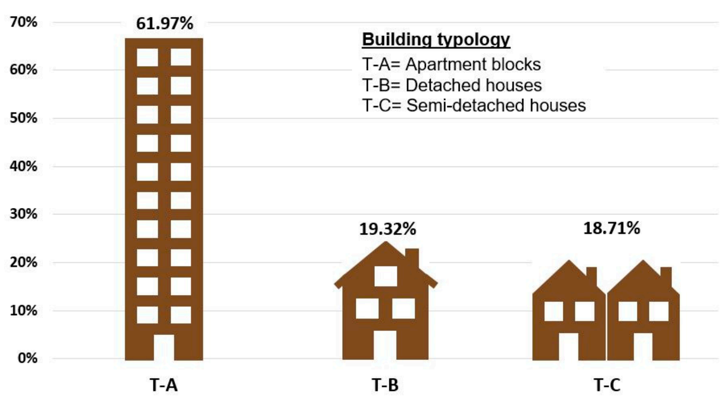

Figure 3. Percentage of construction flaws by building typology.

In order to review the breakdown of type of construction flaw and type of pathology origin for each of the three building typologies, Table 2 was produced, showing the percentage of cases according to each type of construction flaw and to the total of the studied set.

Table 2. Percentage of construction flaws by building typology and pathology origin.

COD.-T	Icon	CF1			CF2			CF3			CF4		
		PCM	CPA	ST	PCM	CPA	ST	PCM	CPA	ST	PCM	CPA	ST
T-A		35 (1.4)	10 (0.4)	45 (1.8)	44 (5.6)	35 (4.4)	79 (10.1)	7 (2.6)	49 (18.7)	55 (21.3)	9 (4.0)	55 (24.7)	64 (28.8)
T-B		20 (0.8)	5 (0.2)	25 (1.0)	5 (0.6)	3 (0.4)	8 (1.0)	2 (0.8)	19 (7.2)	21 (8.0)	2 (0.8)	19 (8.5)	21 (9.3)
T-C		25 (1.0)	5 (0.2)	30 (1.2)	11 (1.4)	2 (0.2)	13 (1.6)	4 (1.4)	20 (7.6)	24 (9.1)	1 (0.6)	14 (6.2)	15 (6.8)

Abbreviations: CF1: Condensations. CF2: Fissures. CF3: Humidity. CF4: Infiltrations. COD.-T: Code of building typology. PCM: Properties and characteristics of materials. CPA: Conditions of placement and application. ST: Sub-total. T-A: Apartment blocks. T-B: Detached houses. T-C: Semi-detached houses. Note: All values are expressed in percentage, according to the cases found. The upper value refers to the total of each type of construction flaw, and the value in parentheses refers to the total of the studied set (number of cases in the research).

From this table it can be seen that the highest percentage for a type of construction flaw is 55%, referring to 'infiltrations in apartment blocks due to conditions of placement and application': CF4/T-A/CPA. The following, with 49%, is humidity which takes place in the same building typology and with the same pathology origin: CF3/T-A/CPA. In turn, the lowest percentage for a construction flaw (1%) is obtained for 'infiltrations in semi-detached houses due to conditions of placement and application': CF4/T-C/PCM. When observing the percentages within the total 497 cases analyzed, we see that the highest value is also obtained in 'infiltrations in apartment blocks due to placement and application issues', with 24.7%: CF4/T-A/CPA.

3.3. Cases by Pathology Origin

The results obtained by pathology origin were as follows: 'conditions of placement and application' 392 cases (CPA) and 'properties and characteristics of materials' 105 cases (PCM). The percentages are shown in Figure 4. In each figure is also included the breakdown by building typology, it being apparent that the most important values obtained are T-A/CPA (49%), T-B/CPA (16%) and T-A/PCM (14%).

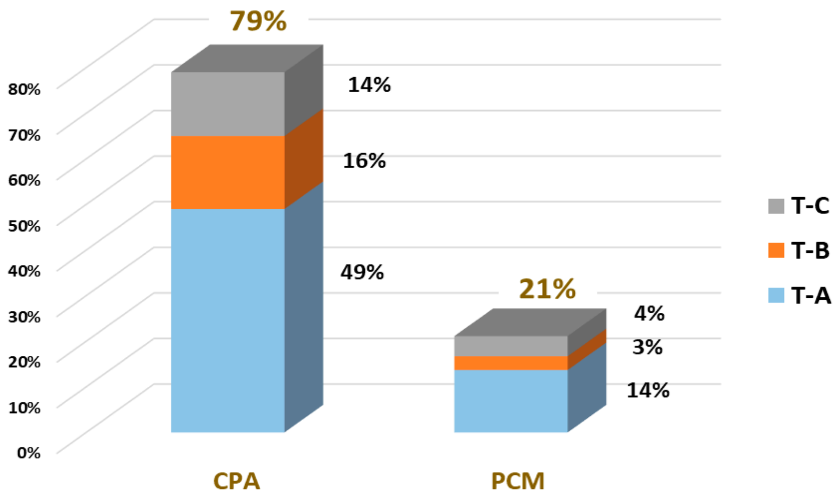

Figure 4. Percentage of cases by pathology origin and building typology.

3.4. Determination of Categories of Lawsuit Risk

From the descriptors outlined in the methodology (type of construction flaw, pathology origin, and building typology) a procedure has been implemented for the numerical calculation of 5 stages to quantify the level of presence and importance of the 'interrelations' between them (see Section 2.3: second phase of the research). Table 3 expresses the values for these 5 stages, eventually arriving at the different 'risk categories' of lawsuits by owners—in other words, the probability of lawsuits referring to construction flaws according to the nature and recurrence of the interrelations of these descriptors.

According to the range of values obtained, the following categories are established: Very High (VH), High (H), Moderate (M), Low (L) and Very Low (VL). Based on these, the last section of Table 3 shows which interrelations are most recurring. These categories quantify into 5 ranges the entire process of the preceding stages, it being observed that, in the majority of times, the interrelations have a low level of presence (VL category) and they are the most numerous (with 12 types of interrelations). On the other hand, the category with the highest level of presence, and therefore of highest risk (VH: $F \geq 400$), takes place in only one type of interrelation: Infiltrations in apartment blocks, caused by conditions of placement and application (CF4/T-A/CPA = 691.6).

Table 3. Determination of the level of risk of lawsuits by owners.

STAGE	CONCEPT			VALUES			
'Scoring' according to the degree of the problem (STAGE 1)	Type of score			Value per descriptor			
	Score according to nuisance to owners			CF1	CF2	CF3	CF4
				3	1	5	7
	Score according to technical importance			PCM	CPA		
				2	4		
'Level of joint severity' between construction flaw and pathology origin (STAGE 2)	Combined score for each interrelation			Type of construction flaw			
				CF1	CF2	CF3	CF4
	Pathology origin		PCM	6	2	10	14
			CPA	12	4	20	28
'Interrelation and intensity matrix' between construction flaws, building typology and pathology origin (STAGE 3)	Presence of each interrelation (%)			Type of construction flaw			
				CF1	CF2	CF3	CF4
	Building typology and pathology origin	T-A	PCM	1.4	5.6	2.6	4.0
			CPA	0.4	4.4	18.7	24.7
		T-B	PCM	0.8	0.6	0.8	0.8
			CPA	0.2	0.4	7.2	8.5
		T-C	PCM	1.0	1.4	1.4	0.6
			CPA	0.2	0.2	7.6	6.2
'Weighted risk matrix for lawsuits' to determine the risk factor –F–(STAGE 4)	Presence of each interrelation			Type of construction flaw			
				CF1	CF2	CF3	CF4
	Building typology and pathology origin	T-A	PCM	8.4	11.2	26.0	56.0
			CPA	4.8	17.6	374.0	691.6
		T-B	PCM	4.8	1.2	8.0	11.2
			CPA	2.4	1.6	144.0	238.0
		T-C	PCM	6.0	2.8	14.0	8.4
			CPA	2.4	0.8	152.0	173.6
'Risk categories' of lawsuits by owners (STAGE 5)	Determination according to the value of risk factor						
	Category	Code	Condition	No. interrelations (Figure 5a)	No. cases (Figure 5b)		
	Very High	**VH**	$F \geq 400$	1 interrelation	123 cases	F = risk factor, according to Stage 4	
	High	**H**	$170 \leq F < 400$	3 interrelations	166 cases		
	Moderate	**M**	$25 \leq F < 170$	4 interrelations	107 cases		
	Low	**L**	$10 \leq F < 25$	4 interrelations	61 cases		
	Very Low	**VL**	$F < 10$	12 interrelations	40 cases		

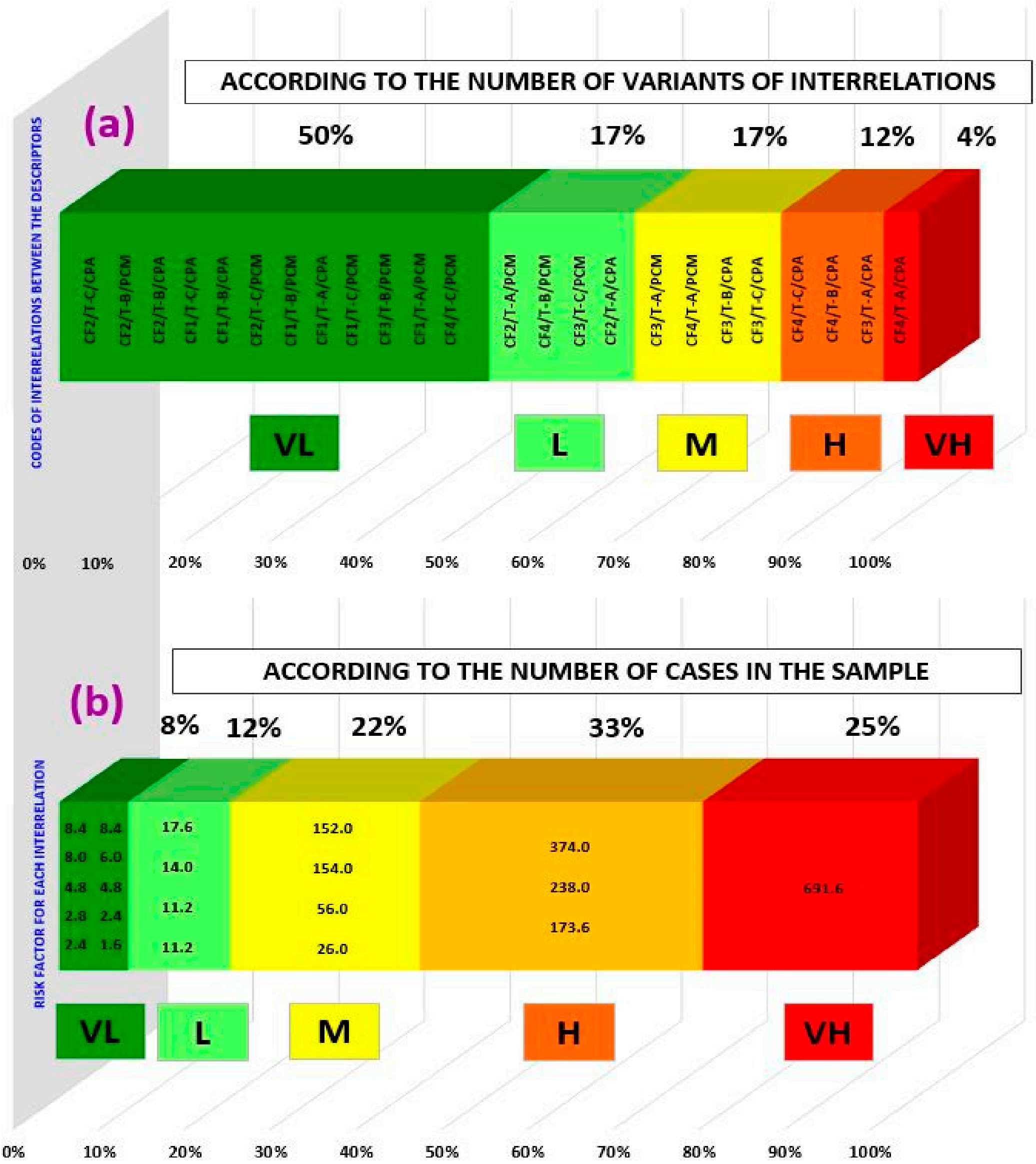

Figure 5. Assignment of each of the interrelations to each of the five existing risk categories. Upper part (**a**) according to the number of interrelations and lower part (**b**) according to the number of cases).

In second place is category H, with these 3 types of interrelations:

- Humidity in apartment blocks, caused by conditions of placement and application (CF3/T-A/CPA = 374);
- Infiltrations in detached houses, caused by conditions of placement and application (CF4/T-B/CPA = 238);
- Infiltrations in semi-detached houses, caused by conditions of placement and application (CF4/T-C/CPA = 173.6);

Based on these interrelations, we can see that some descriptors are more dominant than others. In this sense, the most dominant is pathology origin (present in the 4 cases with highest F), followed by the type of construction flaw (in 3 out of the 4 cases with highest F) and, finally, building typology (in 2 out of the 4 cases with highest F).

The aforementioned results lead the authors to understand that roof designs in Spain should be especially careful about their technical prescriptions and, specifically, about substantially improving [47] aspects related to tail-ends which may lead to infiltrations and entry of water, as also occurs in other countries [15]. In this regard, for [48], the main reasons for problems in buildings are defects in the design stage and in the execution stage, representing the great portion of subsequent construction flaws. They found, indeed, that flaws caused by the materials themselves, by poor usage during the service life, and by atmospheric agents represent a much smaller percentage of the total.

For a better understanding, Figure 5 was produced, showing the assignment of each of the interrelations defined in stage 4 of Table 3 to each of the five risk categories defined in stage 5 of this same table. In this manner it can be defined/considered that the risk for the interrelations within VL is 'negligible', that for category L it is 'acceptable', for M it is 'standard', for V it is 'extreme' and for VH it is 'critical'. Sub-Figure 5a also expresses the percentage that represents the total number of interrelations of each category, according to all 24 types of interrelations (the greatest is VL = 50%). Within the graphical area of each category are included the references of each interrelation, formed by the 3 descriptors which define them (construction flaw/building typology/pathology origin); in this way a univocal identification is obtained for each. These identifications are sorted in increasing order (with the lowest value for risk factor F having placed next to the *Y* axis).

A second part of the chart, sub-Figure 5b also shows the five risk categories, expressing the percentage relative to the number of cases assigned to each of those categories (indicated in the second to last column of Stage 5 of Table 3). In this way, category VH, which obtains 4% in sub-Figure 5a (1 interrelation out of 24), represents 25% (123 out of 497 cases) in sub-Figure 5b. Here we can see that categories VH and H, with only four types of interrelations between them, total 289 cases (58% of the studied total); this demonstrates the true dimension of this construction problem. In this part of the chart are also included the values for the risk factor F within each category.

3.5. Analysis by Demographic Aspects

We shall define as 'combinatorial correlation' (not to be mistaken for 'interrelations') the concordance between construction laws and the three demographic aspects indicated in Table 1 (population—number of inhabitants [P], number of houses [H] and gross domestic product per capita [G]), giving way to numerous possibilities for combinations between these concepts. Table 4 shows a breakdown of these correlations (54 in total), sorted by P-H-G-CF, so as to present the distribution of cases according to these demographic aspects and determine where there is a higher percentage of prevalence related to them. In other words, it is a way of shedding light on how these demographic parameters, external to the buildings, can influence the construction flaws analyzed.

The first observation is that there is a marked dependency between demographic aspect 2 (number of houses [H]) and demographic aspect 1 (population—number of inhabitants [P]) which, in fact, is logical. In this way, it can be highlighted that all construction flaws existing in P4 exist only in H4 and G4. On the other hand, P3 takes place 3 out of 4 times in H3, and 1 out of 4 times in H4. These values indicate that there is a tendency of concentration when P, H and G are simultaneously high. It can also be noted that in locations with higher populations (P4) there is only one combinatorial correlation for each type of construction flaw (all associated to H4 and G4: P4-H4-G4). These flaws are: P4-H4-G4-CF1 (2 cases; 0.40%), P4-H4-G4-CF2 (10 cases; 2.01%), P4-H4-G4-CF3 (29 cases; 5.84%) and P4-H4-G4-CF4 (47 cases; 9.46%).

If the risk categories (VH, H, M, L and VL) are added to the combinatorial correlations indicated, now sorted by CF-P-H-G instead of by P-H-G-CF (research variable not included in Table 4 to not make its visualization more complicated), 108 different possible correlations would result. In this situation, it should be highlighted that risk category VH occurs only with construction flaw CF4, while risk category H occurs 56.0% of the time with CF3, and 44.0% of the time with CF4. Equally, category M does not exist in CF1 and CF2 (given that CF3 = 81.3% and CF4 = 18.7%).

Table 4. Combinatorial correlation between P/H/G/CF.

Population (p)	% Popul.	Houses (h)	Houses	Gross Dom. Prod. Per Capita	% Gross Dom. Prod. Per Capita	Const. Flaw (cf)	% Cases
P1	13.06%	H1	11.86%	G1	2.01%	CF1	0.20%
						CF2	0.20%
						CF3	0.40%
						CF4	1.21%
				G2	3.62%	CF1	0.20%
						CF2	0.20%
						CF3	1.41%
						CF4	1.81%
				G3	2.01%	CF2	0.20%
						CF3	1.01%
						CF4	0.80%
				G4	4.22%	CF1	0.40%
						CF3	1.41%
						CF4	2.41%
		H2	1.20%	G2	1.20%	CF3	0.40%
						CF4	0.80%
P2	36.82%	H1	0.20%	G2	0.20%	CF4	0.20%
		H2	36.62%	G1	6.03%	CF1	0.60%
						CF2	1.21%
						CF3	2.41%
						CF4	1.81%
				G2	12.88%	CF1	1.01%
						CF2	1.21%
						CF3	5.63%
						CF4	5.03%
				G3	7.85%	CF1	0.60%
						CF2	1.81%
						CF3	2.62%
						CF4	2.82%
				G4	9.86%	CF1	0.20%
						CF2	1.41%
						CF3	5.23%
						CF4	3.02%
P3	32.4%	H3	24.16%	G1	3.22%	CF1	0.20%
						CF2	0.40%
						CF3	1.21%
						CF4	1.41%
				G2	11.68%	CF1	0.20%
						CF2	1.81%
						CF3	3.62%
						CF4	6.05%
				G3	6.24%	CF2	0.40%
						CF3	2.82%
						CF4	3.02%
				G4	3.02%	CF2	0.20%
						CF3	1.21%
						CF4	1.61%
		H4	8.25%	G3	8.25%	CF2	1.61%
						CF3	3.22%
						CF4	3.42%
P4	17.7%	H4	17.71%	G4	17.71%	CF1	0.40%
						CF2	2.01%
						CF3	5.84%
						CF4	9.46%

Based on all of the above, it can be stated that there is a clear relation between lawsuits and the demographic values of population, number of houses and gross domestic product per capita). According to this relation, the more significant the demographic conditions are, the greater is the theoretical risk of lawsuits. Thus, based on the percentages of cases in Table 4, it can be seen that the combinatorial correlation with the lowest population values (P1 combined with the other demographic conditions) have an average percentage of cases of about 1%. In turn, the combinatorial correlation with moderate population values (P2 and P3 combined with the other demographic conditions) have an average percentage of cases of about 2%. Finally, the combinatorial correlation with the highest population values (P4 combined with the other demographic conditions) have an average percentage of cases of about 4%.

This typology of correlations was not found in other papers, in order to allow for a comparison to evaluate possible similarities or differences. As such, the authors believe that this system may serve as a basis for future research that may be produced in other countries and want to consider this procedure as a means of correlating their data sources.

4. Discussion

The results of this analysis express that the highest risk categories (VH, H and M) concentrate most cases (123, 166 and 107, respectively), representing 4/5 of the total. It is likewise noted that there is a high casuistry, given that the same typologies of problems take place recurrently. In this way, the interrelation CF4/T-A/CPA (flaws by infiltrations in apartment blocks and with pathology origin due to conditions of placement and application) represents the totality of the cases in category VH, reaching 123 in number, which indicated that designs and construction projects repeat the same defects over and over again. An analogous analysis is applicable to what occurs with the 3 interrelations of which category H is composed.

Furthermore, according to the percentage distribution expressed in Table 4, it can be seen that improvements in the per capita economy and location of more or less large populations lead to a greater incidence of lawsuits. While it may appear obvious, it was noted that an environment with higher social demands over competitiveness and awareness of economic efficiency (which are usually more easily manifested in P4 and G4), as well as a lesser relation between owners and remaining stakeholders of the construction process (more common in larger cities), leads to a higher probability of lawsuits.

Due to the extension and representativeness of the studied set, all these results lead the authors to consider that there is a high potential for vulnerability in flat roofs built in Spain, with the consequent number of conflicts which require resolution. As such, it would be very appropriate to take preventative measures to reverse this situation.

For many, construction flaws could be significantly reduced with the total implementation in the construction process of a technology which is widely adopted in other European countries: BIM methodology [49], the adoption of which is expected to grow by 22% worldwide in 2019. It is, therefore, a preventative way of responding to the great number of construction flaws analyzed herein. For this reason, the Spanish insurance company MUSAAT has recently sponsored some editions of certain international congresses on BIM, such as the 'European BIM Summit' and 'EUBIM' and, beyond that has launched a new insurance policy for professionals using this methodology. This insurance company understands that, commercially, it is possible for technicians to pay less when working with BIM, given that there is a lower probability of construction flaws (and, in general, fewer incidents). Nevertheless, this methodology is not yet widely used in Spain, despite plans for making its implementation mandatory in public works throughout 2019 [50]. In addition to the above, the use of BIM supposes savings in the design process of between 20% and 30% [51].

One should also bear in mind the consequences of the complexity and delays inevitably associated with most processes of determination of causes and responsibilities of construction flaws in buildings, which is added to a generalized absence of channels of information about these cases. All of this makes it so that, in general, participants are unaware of the risks which many solutions imply and, in particular, leads designers to not have an effective self-evaluation and feedback mechanism to prevent designs from leading to the same construction flaws. In this regard, it is considered that implementing external and specialized prior supervision of roof designs [47] is an excellent way of minimizing the flaws which might subsequently arise [36]. If, in addition, a real and comprehensive control were carried out during the execution stage, the number of cases found herein would have been far lower [52].

In turn, measures to solve proceedings in more flexible, fast and economic ways should also be emphasized. It is the case of civil and commercial mediation processes, instead of systematically filing lawsuits for any problems, from the start. Nevertheless, in certain aspects there is a belief that, where there is a damage, there should be someone guilty—a perspective widely generalized in Spain in recent times. People believe that, when they hire a professional (such as an architect or an engineer), and they are supported by an insurance policy, it should always be the insurance company paying in the event of a problem—this concept makes it very risky to resort to a mediation process given such misconceptions [53]. All of this can lead to the consolidation of an unsustainable judicialization system. Sustainability, therefore, can be seen from different points of view, including in themes such as culture [54].

5. Conclusions

This research is based on an unprecedented data source and methodology, of which were found no precedents in other countries: expert reports used during lawsuits. The results obtain therefrom and contained in the rulings of Spanish courts of law, demonstrate this to be a procedure of great interest to forensic engineering. Furthermore, the high number of cases analyzed (497) makes this study highly characteristic of what is currently taking place in the building sector in Spain (it being pointed out, furthermore, that the presented values correspond to 100% of the data existing for the period being studied). As such, this approach is considered to be of great usefulness to facilitate the reduction of future construction flaws, mitigating the wide-ranging economic, social, and environmental consequences arising from interventions in a high-impact field such as buildings.

The risk of lawsuits by owners has been determined, according to the degree of nuisance supposed by construction flaws, as well as to their technical importance. Based on these, it is possible to predict a higher or lower probability of a construction flaw occurring in flat roofs, and of it reaching the courts. The highest value obtained for the 'risk factor' is F = 691.6, referring to 'Infiltrations' (CF4) appearing in 'apartment blocks' (T-A), resulting from 'conditions of placement and application' (CPA). Based on said risk factor (F), it has been noted that the highest risk categories (VH, H and M), according to the number of cases, concentrate 80% of the total (25% + 33% + 22%, respectively), which indicates a worrying level of presence for the construction sector, with regard to the low quality of construction.

Complementarily, the percentages of distribution of the number of cases according to the population—number of inhabitants (P), number of houses (H) and gross domestic product per capita (G) were equally determined. It is noted that there is a higher prevalence in locations where the values of P, H and G tend to be high or very high. It has thus been empirically observed that higher purchasing power and urban concentration lead to an increase in the level of demand over a product (in this case, flat roofs), consequently resulting in lawsuits. Future works could open new lines of research to include the values of these demographic conditions in the numerical process of calculation presented herein.

The data and methodologies in this paper constitute a novel contribution to engineering and to construction management, enabling designers and supervisors to make decisions on flat roofs as well as facilitating the identification of conditions intervening in a better and greater durability of the system. These represent a contribution towards optimizing building operation during their service life, amounting to a key factor in the sustainability of building processes.

The authors understand that these results can be extrapolated to other countries, especially those in the European Union, given the analogy between construction systems used, the existence of a basic common legislation for the free circulation of persons and goods, as well as the growing standardization of construction systems and products. In addition, by establishing a new tool for the determination of the risk of appearance of construction flaws in flat roofs, this research makes it possible for other authors to implement the same methodology to quantify the cases occurring in their respective countries.

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