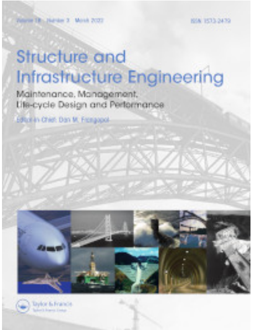

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ABSTRACT

In the context of the existing buildings, in recent years the concept of maintenance has changed from corrective maintenance to preventive maintenance, which is based in part on periodic inspections. There is ample evidence that preventive maintenance is more efficient than corrective maintenance, since severe deteriorations that may represent danger to people are avoided, and also money is saved. To make periodic inspections of the buildings is useful to quantify the extent to which deteriorations are severe or not, in order to facilitate decision making and prioritise therapeutic interventions. To this purpose, many scales have been used and are used to assess the degree of severity of the deteriorations in constructive elements. But it is important to say that there is no common consensus and these scales are different between them according to the study to which they belong. Thus, the main goal of this article is to propose a methodology for calculating the degree of severity of damages in buildings, which is of widespread use. This calculation method, based on one hand in a distribution of values and on the other hand in a single value (scalar), lets to calculate the severity index of systems and of the entire building, and it is easy to use and flexible.

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Scale; severity index; damages; direct assignment method; system; variables; attributes; quartiles

1. Introduction

The interest in the evolution of the building and infrastructure stocks has been evolving during the time (Kohler & Yang, 2007), in some cases closely linked to the sustainable development debate in the last years (Kohler & Hassler, 2002). Similar conclusions can be derived from historical data obtained for residential and non-residential buildings (Algreen-Ussing, Hassler, & Kohler, 2004). A central issue is the mortality of buildings. Lifetables of classical population dynamics (Klein & Moeschberger, 2003) can be used for estimating the mortality of a sample of building and infrastructure stocks (Herz, 1998; Schiller, 2007).

In the same way, there are several authors who study construction defects, usually focussed on deteriorations that have appeared in buildings due to lack of maintenance, project error, execution failure, material defect, inappropriate use, etc. Some of these deteriorations are for example the following: failure in the adhesion of the outer ceramic cladding (Chew, 1999), moisture (Chew, 2005), deteriorations in roofs (Garcez, Lopes, de Brito, & Silvestre, 2012; Garcez, Lopes, de Brito, & Sá, 2012), deteriorations in natural stone coverings (Neto & de Brito, 2012), deteriorations in gypsum pastes for partitions and ceilings (Pereira, Palha, de Brito, & Silvestre, 2011), deteriorations in ceramic coatings (Silvestre & de Brito, 2009), deteriorations in ceramic façade claddings (Silvestre & de Brito, 2011), deteriorations in the natural stone cladding (Silva, de Brito, & Gaspar, 2011), deteriorations on the envelope of buildings (Rodrigues, Teixeira, & Cardoso, 2011), deteriorations in façades (Ruiz, Aguado, Serrat, & Casas, 2019a), deteriorations in wood structures (Rodriguez, 1998), deteriorations in load-bearing rammed earth walls (Ruiz, 2013), problems in the subsoil (Díaz, et al., 2015), etc.

On the other hand, the rapid industrialisation and population migration of the last 30 years, has led to fast growing urbanisation, doubling the building and partially the infrastructure stocks in very short periods (20–30 years) (Yang, 2006). The rate of change is very high and it is not always known, how well these stocks are constructed.

In this context, the crucial indicator is the deterioration index of the different components of the stock (Kohler & Yang, 2007). Likewise, 'What is not defined can not be measured. What is not measured cannot be improved. What is not improved always deteriorates'. This phrase is from Sir William Thomson, Baron Kelvin of Largs. Although the phrase is from the nineteenth century, it is fully in force, and we are well aware of the importance of performing preventive maintenance in buildings in order to prevent their degradation and the appearance of severe deteriorations. In the framework of maintenance is true that to make periodic inspections of buildings, is useful to quantify the extent to which deteriorations are severe or not, in order to facilitate decision making and prioritise therapeutic interventions. In fact, many scales are used to assess the severity index of the constructive elements. But there is no common consensus and these scales are different from each other according to the study to which they belong (Ruiz, 2014).

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All the referred shows the need to propose and validate a scale, in order to assess the severity index of constructive elements in buildings, which is of widespread use. Thus, the main goal of this article is to propose a calculation method, based on one hand in a distribution of values and on the other hand in a single value (scalar), to calculate the degree of severity of systems and of the entire building, easy to use and flexible.

In addition, the proposal has also implications in terms of efficiency. Indeed, to facilitate decision-making to ensure that decisions are optimal, that is, they are not insufficient but neither excessive, it is achieved to be economically more efficient. Furthermore, it is demonstrated that preventive maintenance is more economically efficient that corrective maintenance. Related with this approach, the proposal also is useful to establish a rehabilitation program, defining different phases, ordered according to their degree of priority, which in turn is related to the degree of severity. The rehabilitation program also has economical advantages, by allowing the total cost of the rehabilitation to be paid in different phases.

2. Other kind of scales

The technical interest in defining the degree of damage produced by any cause (earthquake, hurricanes, etc.) is well known. Consequently, the need to define scales of damage arises. One of the first parts of this research was to study the characteristics of existing scales in the general framework, which are commonly accepted and used. The criteria for selecting this scale was based on the following two main aspects: a) They are sufficiently representative and accepted, widely used in their respective fields; b) They belong to various fields of science, in order to get an approach with a wide perspective.

Some of the studied scales, among others, were the following: Beaufort (measuring wind intensity) (Friendly, 1973), Fujita-Pearson (intensity of a tornado) (Fujita, 1971), Richter (intensity of earthquakes) (Gutemberg & Richter, 1954), Modified Mercally (intensity of earthquakes) (Richter, 1958), Mohs (hardness of a substance) (Hofmann & Karpinski, 1980), VAS (degree of pain) (Von Korff, Ormel, Keefe, & Dworkin, 1992), Norton (risk for pressure ulcers) (Panagiotopoulou & Kerr, 2002), Glasgow (grades of coma) (Gabbe, Cameron, & Finch, 2003), etc.

The range of values of these scales is diverse, having scale with a range of values from 0 to 10 (VAS), from 0 to 12 (Beaufort, Fujita-Pearson), from 5 to 20 (Norton), etc. Another important aspect of the study of these scales is that in some of them variables are measured (Beaufort, Fujita, Douglas, Richter, etc.) which are easily measurable with the proper equipment, thus the level of certainty to assign values is very high. In the other scales (Modified Mercally, Mohs, VAS, Norton, Glasgow, etc.) attributes are measured, which in some cases are easily measurable, as happens in the Mohs scale, but in some other cases the measurement of the attributes may have high variability or subjectivity, as happens in the VAS scale.

In the scope of damages in buildings, the level of certainty to assign values will not be a priori very high, since to assess the degree of severity of a component (either a beam, a balcony, a cornice, a bearing wall, etc.) may be subject to some degree of variability. Therefore, the scales that a priori can be more useful for our proposal are the Modified Mercalli scale, the VAS scale, the Norton scale and the Glasgow scale, especially the last 3 (associated with the field of medicine), since they have also some degree of variability to assign values in the diagnosis of people, some of them in emergency conditions. This field of medicine has important conceptual similarities with the field where the proposed scale belongs, which is the diagnosis of building elements.

In the same way as explained earlier, we have also studied scales of the field of construction. The description and analysis of scales has been extended to the scope of the bridges, because of conceptual similarities in the evaluation systems. These studied scales have no specific names, in contrast to the previously nine studied scales that do have (Boufort, VAS, Richter, etc.). From these studied scales, it is observed that there are significant differences between them, with respect to the used indicators (Bordalo, de Brito, Gaspar, & Silva, 2011; BRIME, 1999; Elhakeem & Hegazy, 2012; Ferreira, Silva, de Brito, Dias, & Flores-Colen, 2021; Ferreira, Canhoto Neves, Silva, & de Brito, 2018; Flourentzou, Brandt, & Wetzel, 2000; León, 2006; Noor et al., 2019; Roche, 2008; SAMARIS, 2005; Serrat, Gibert, & Jordana, 2009; Thiel, 2008; Uzarski & Grussing, 2008, among others). Thus, with respect to the differences in the range of values should be noted that it goes from 3 to 100 values (Ruiz, Aguado, Serrat, & Casas, 2019b); understood that a range of 3 values is too small to represent the different cases and grades of gravity, while on the other hand, we consider that a range of 100 values is excessive, due to be questionable the human appreciation of the qualitative difference between a value and the next since it is almost negligible.

Owing to what is valued in this issue are attributes (severity index of constructive elements), a priori diffuse and subject to some degree of variability, to specify very small qualitative differences between values it is something that is not credible. It is important to say that in all the studied scales in the scope of construction, and also in the general scope, the metric (number of degrees) of these scales is based in the opinion of the authors, not in any methodological process. Ruiz et al. (2019b) developed a methodology in order to calculate the optimal metric (number of degrees) of a scale in the scope of construction.

Another observed difference is the method of application to determine the value of severity index: direct assignment (DA) (Voodg, 1983) or application of mathematical functions or algorithms (AFM) (Papadrakakis, Lagaros, Tsompanakis, & Plevris, 2001). It is considered that the first method has the advantage of being faster and easier to use by the technicians, while it has the disadvantage of greater variability may exist in the assignment of values. The second method has the disadvantage of being more laborious and complex to implement by the technicians, meanwhile it has the advantage of reducing the degree of variability. Thus, on the proposed scale should be positive that it is flexible in order that the two methods can be applied. The technician will apply a method or the other depending on the object of the study, the degree of accuracy necessary and the time considered appropriate to dedicate to it (Ruiz, 2014).

In most of the studied scales, there is not a methodology to calculate the severity index of a system or of the entire building. In the few scales where there is a method, the values resulting are scalars, which do not show the variability or the distribution of severities. The proposed methodology in this paper lets to show the variability or the distribution of severities. It is also remarkable to highlight that unlike what happens in other areas of science where there are, as we have seen, scales widely used and commonly accepted, in the field of the buildings there is not a common scale for assessing the degree of severity of the constructive elements, and there are many different scales. It is clear that, as happens in other areas of science, in the field of the buildings would be very useful to have a common scale and a methodology widely used to assess the severity index of the buildings.

3. Proposal for calculating the degree of severity of damages in buildings

3.1. Areas of application

This section explains the proposed methodology for calculating the degree of severity of damages in buildings as a whole (biggest proposed unit) or parts thereof, which will be called systems (*S*). It is considered appropriate to propose a reasonable division of building into the systems, which is presented in Table 1. In order to provide flexibility to the methodology it allows that the total number of systems and the definition of them can be chosen by the technician that develops the study of the building, thus the proposed method is of general application. Therefore, the building as a whole is the sum of the systems that constitute it, as indicated as follows:

$$\text{Building}: \quad (B) \; = \sum_{i=1}^{n} (S)_i \tag{1}$$

Each system can be divided into zones which constitute the last and smallest proposed unit to value. A zone is defined as a specific part of a constructive element, as for example an area of a wood beams floor, an area of a façade, an area of a reinforced concrete beam floor, an area of a balcony, etc. Figure 1 shows some images that represent what is named zone.

Thus, the set of zones into which the system has been divided (p), constitutes the entire system, as follows:

$$\text{System}: \quad (S)_i = \sum_{j=1}^{p} (Z)_j \tag{2}$$

One important point is that this methodology can be applied to any kind of existing scale of severity of damages in buildings, regardless they are based in DA method or in AFM method or in both. As it has been seen in Section 2, there are several scales of severity of damages in buildings, with important differences between them.

In order to facilitate the comprehension of the proposed methodology, in this research work it has been also proposed a scale of severity of damages in buildings. This proposed scale ranges from value 0 (zero gravity and the constructive element is in perfect condition) to value 10 (extreme gravity; it is not conceivable a greater gravity; pathology in terminal phase; collapse may occur at any time). We denote the grade or index of severity with the letter G. The proposed scale explains in a general way what it means or represents each degree, in order to reduce the variability among different technicians when assigning values. Owing to the scale is applicable to any type of constructive element (walls, beams, columns, bearing walls, façades, etc.), definitions are necessarily generic. These definitions can be seen in Ruiz et al. (2019b).

In order to facilitate the visualisation of the distribution of gravities of a constructive element we propose that maps can be performed with level curves, corresponding to different G values, regardless of whether the studied element is a beam, or a whole floor, etc. For greater visibility, we propose that each G value is associated to a colour.

3.2. Proposed application methodology

The proposed methodology, which is presented schematically in Figure 2, it is initiated by the direct assignment method (DA) based on the generic definitions of the reference scale, through which the grade or index of severity, *G*, is assigned to zones *j* of the building. The severity index of a zone *j* is denoted G_j. In the variant called (a), the process ends here, which is in cases where the object of study is assessing the gravity of different zones of the building, but it is not necessary to evaluate the overall gravity of a system or of the whole building.

The next step of the methodology, when required, is to assess the severity of one or more systems, for which there are the variants called (b) and (c). In variant (b) DA method based on the generic definitions of the proposed scale is used, through which the degree of severity of the considered system is assigned. In variant (c) the calculation method that it is proposed in the next subsection is used, applying it to the G_j values comprising the zones of the system, which allows to calculate the degree of severity of the considered system.

The variant (b) is of application in cases where the object of the study is such that it is necessary to spend a short time. Some of these cases may be the following: i) Global study of an urban area, in which it is necessary to assess the grade of gravity of hundreds or thousands of façades; ii) Emergency interventions, such as civil service technicians or firemen in cases of sever deteriorations with potential risk for people. The variant (c) will be of application in the remaining cases in which is required to determine the grade of gravity of a system or building.

Table 1. Proposal of building systems.

System	Description	Main constituent parts
1	Façades	Claddings, base material, cantilevers, cornices, windows and other practicable openings, railings, balustrades, ornamental elements, etc.
2	Vertical structure	Pillars, load walls, foundation, etc.
3	Horizontal structure	Beams, beam filling, vaults, arches, etc.
4	Roofs and inner courtyards	Roof tiles, pavements in flat roofs, waterproofing, thermal insulations, skylights, walls and practicable openings for inner courtyards, etc.
5	Interior building elements	Partitions, interior walls, practicable openings, pavements, interior claddings, etc.
6	Staircases	Walls, stair structure, steps, railings, etc.
7	Sewer facilities	Downpipes, drains, gutters, etc.
8	Other facilities	Electricity, water, gas, elevators, etc.

Figure 1. Images of four zones of construction elements.

3.3. Calculation of the resultant severity of the system

Within the framework of variant (c) in Figure 2, first it should be said that to obtain the resultant severity of a system based on the summation of the G_j values of that system, applying a weight w_j that is based on the area or proportion of the zone j (A_j) regarding the area or whole unit (A_T) of the considered system, gives adequate results only for cases that severity of the system is homogeneous, for example if the entire system is heavily deteriorated or everything is in good condition. However, it gives inadequate results in cases where there is significant variability of severity in the system, especially in cases of extreme variability.

For this reason, after discarding the previous method of calculation for being inadequate, in order to calculate the resulting severity of a system s it is proposed a method based on statistical quantiles. In this case, quartiles are used as well as the minimum and maximum values of G_j of the analysed system, allowing to define the distribution of severity of system s, $G_d^{(s)}$, as follows:

$$G_d^{(s)} = (q_0^{(s)}, q_{0.25}^{(s)}, q_{0.50}^{(s)}, q_{0.75}^{(s)}, q_{1.00}^{(s)}) \quad (3)$$

where $q_0^{(s)}$ and $q_{1.00}^{(s)}$ are the minimum and maximum value, respectively, of G_j of the system s, and $q_{0.25}^{(s)}$, $q_{0.50}^{(s)}$, $q_{0.75}^{(s)}$ are

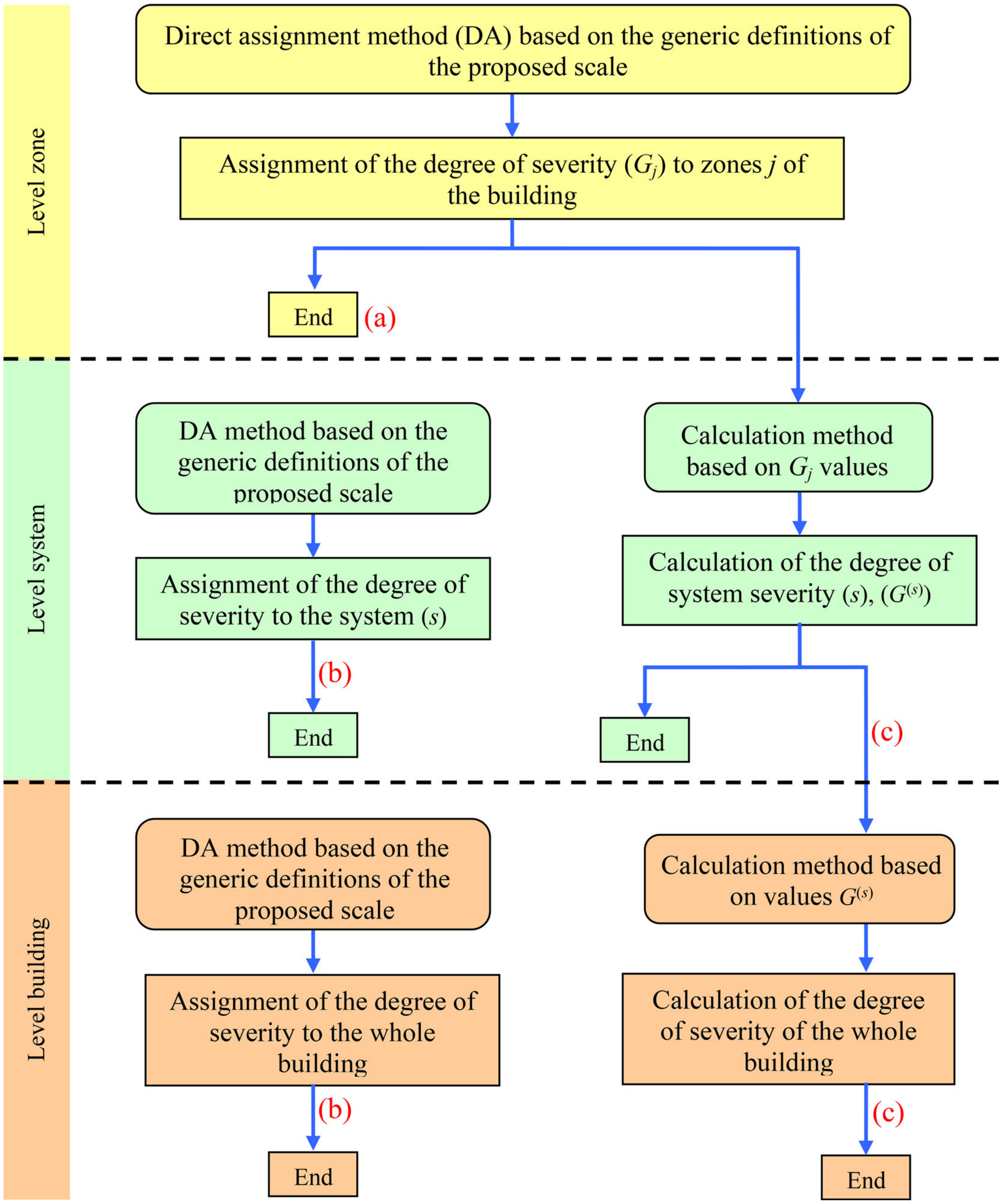

Figure 2. Methodology of application of the proposed scale.
(a) Level zone; (b) DA method; (c) Calculation method

the maximum value of G_j corresponding to the 25%, 50%, 75% less degraded, respectively, of the system s.

With this methodology can be directly observed the highest value of G_j of each of the evaluated systems of the building ($q_{1.00}^{(s)}$). It can be also established whether the extension of the pathologies is generalised or punctual in function of the G_j values, which are derived from analysing these G_j values for the 25%, 50% or 75% of the system. The resulting vector of a system s allows to determine the priority of intervention of the system s, which is determined by the value of $G_{\max}$, corresponding to the last value of the vector. Therefore, low values of $G_{\max}$ indicate that it is not of priority or urgent to intervene in the system s, meanwhile high values of $G_{\max}$ indicate that it is urgent to intervene in the system s. The relation between priority of intervention and $G_{\max}$ values is established in Table 2.

$G_d^{(s)}$ also allows to establish the extension of the corresponding dysfunction to $G_{\max}$, extension that it is denoted by $e(., G_{\max})$, that evaluates the position of the minimum quartile in which the $G_{\max}$ value appears. Formally, it is defined as follows:

$$e\left(G_d^{(s)}, G_{\max}\right) = q, \text{ where } q \text{ is the smallest } q_k \text{ such that } q_k = G_{\max} \tag{4}$$

The relation between the extent of the deterioration, and the $G_{\max}$ and q_k values is shown in Table 3.

Thus, it should be emphasised that the proposed vector $G_d^{(s)} = (q_0^{(s)}, q_{0.25}^{(s)}, q_{0.50}^{(s)}, q_{0.75}^{(s)}, q_{1.00}^{(s)})$ gives a lot of information about the severity of the system s, since besides it shows the minimum and maximum severity of the system, it shows

Table 2. Priority of the intervention.

G_{max}	Priority
0 ; 1	Very low
2 ; 3	Low
4 ; 5 ; 6	Moderate
7 ; 8	High
9 ; 10	Very high

Table 3. Extension of deterioration with G_{max}.

$e(G_d^{(s)}, G_{max})$	Extension
$q_{1.00}$	Low
$q_{0.75}$	Intermediate
$q_{0.50}$	High
$q_{0.25}$	Very high
q_0	Total

the distribution of severities thereof. It must be said that while the vector $G_d^{(s)}$ describes numerically the severity index of a system with sufficient accuracy, the distribution can be interesting to be summarised in a single value. For this it is proposed a method that transforms the vector $G_d^{(s)} \in \{0, \ldots, (10)\}^5$ in a scalar $G_r^{(s)} \in [0,\ 10]$, which it is named resulting severity of the system, and it is denoted by $G_r^{(s)}$.

To estimate the mean value of the distribution and using the relationship $E(X) = \int R(g)dg$ that calculates the expectancy of a positive random variable X (in our case between 0 and 10) as the area under the complementary function of the distribution function ($R\ (g) = 1-F\ (g)$), where F denotes the distribution function, it is proposed that $G_r^{(s)}$ is obtained as a first approximation of the area under the empirical distribution of R from the distribution $G_d^{(s)}$. By construction it takes the values $R(q_0) = 1-0=1$; $R(q_{0.25}) = 1 - 0.25=0.75$; $R(q_{0.50}) = 1 - 0.50=0.50$; $R(q_{0.75}) = 1 - 0.75=0.25$ y $R(q_{1.00}) = 1-1=0$.

Figure 3 illustrates this calculation for the numerical example $G_d^{(1)}= (0,\ 2,\ 5,\ 5,\ 8)$.

As appears from Figure 3, the surface that lies under the function $R(g)$ is obtained from the Equation (5). The different fill colours are intended to facilitate the understanding of the used equation. The surface of each colour corresponds to each member of the summation of the Equation (5):

$$G_r^{(s)} = \overbrace{\left(\frac{q_0^{(s)}+q_{0.25}^{(s)}}{2}\right)\cdot 0{,}25}+\overbrace{\left(\frac{q_{0.25}^{(s)}+q_{0.50}^{(s)}}{2}\right)\cdot 0{,}25}+\overbrace{\left(\frac{q_{0.50}^{(s)}+q_{0.75}^{(s)}}{2}\right)\cdot 0{,}25}+\overbrace{\left(\frac{q_{0.75}^{(s)}+q_{1.00}^{(s)}}{2}\right)\cdot 0{,}25} = \frac{q_0^{(s)}+2q_{0.25}^{(s)}+2q_{0.50}^{(s)}+2q_{0.75}^{(s)}+q_{1.00}^{(s)}}{8}, \quad (5)$$

or equivalently as follows:

$$G_r^{(s)} = \sum_{i=1}^{4} \frac{m_i^{(s)}}{4}, \quad (6)$$

where $m_i^{(s)}$ are the midpoints between the components of $G_d^{(s)}$.

In order to have a greater sensitivity over the parts of the building with greater severity, it is proposed to generalise the Equation (6), so it can be applied a set of coefficients $w_i^{(s)}$, which allows, among other possibilities, to give more weight to the components on the right, which are those corresponding to the highest values G_j of the system. In order to provide flexibility to the methodology, it is proposed that the technician can determine the relative weights $w_i^{(s)}$ to give to each coefficient, under the condition that $\sum_{i=1}^{4} w_i^{(s)} = 1$. These coefficients act on the midpoints $m_i^{(s)}$ between components $q_k^{(s)}$, which allows to obtain $G_{rw}^{(s)}$ ($G_r^{(s)}$ weighted) as follows:

$$G_{rw}^{(s)} = \sum_{i=1}^{4} w_i^{(s)} \cdot m_i^{(s)} \quad (7)$$

Owing to that the method has weighted character, it is denoted WGS (Weighted Gravity System). Note that the Equation (7) allows, on one hand, a homogeneous distribution of weights between systems when $w_i^{(s)} = w_i^{(s')}$, for any pair of systems s and s', and on the other hand, a homogenisation between components when $w_i^{(s)} = 1/4$, thus recovering the particular case of the Equation (6).

As it has been seen, the coefficients $w_i^{(s)}$ allow to give more weight to components on the right, which are those corresponding to the highest G_j values of the system. In order to assign weights to prioritise the values of most severity, and regardless of the system, it is proposed that the weights follow a geometric progression of generic ratio r. For higher r values, the difference between the values of the weights is higher, thus giving more weight to the values of greater severity. The first r value that weighs the most severe 50% manifestly (90% versus 10%) is $r=3$ (highlighted in Table 4), thus it is taken as reference value. However, in order to provide flexibility to the methodology, the methodology allows that the technician can choose the r value that deems most appropriate, from which it is possible to obtain immediately the value of the corresponding weights.

3.4. Calculation of the resultant gravity of the building

After obtaining vectors $G_d^{(s)}$, $s=1,\ldots,\ S$, representing the distribution of the gravity of each system s, it is defined the distribution of severity of the building (G_d^*), as follows:

$$G_d^* = \begin{pmatrix} G_d^{(1)} \\ G_d^{(2)} \\ \ldots \\ G_d^{(S)} \end{pmatrix} = \begin{pmatrix} q_0^{(1)} & q_{0.25}^{(1)} & q_{0.50}^{(1)} & q_{0.75}^{(1)} & q_{1.00}^{(1)} \\ q_0^{(2)} & q_{0.25}^{(2)} & q_{0.50}^{(2)} & q_{0.75}^{(2)} & q_{1.00}^{(2)} \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ q_0^{(S)} & q_{0.25}^{(S)} & q_{0.50}^{(S)} & q_{0.75}^{(S)} & q_{1.00}^{(S)} \end{pmatrix} \quad (8)$$

Therefore, G_d^* is a SX5 matrix, grouping by rows the severity distributions of each of the systems. This method is denoted GBD (Gravity Building Distribution).

It should be emphasized that the proposed matrix G_d^* gives a lot of information about the gravity of the building, since besides it shows the minimum and maximum severity of each system, it also shows the distribution of severities of each system. It must be said that while the matrix describes numerically the severity of a building with sufficient precision, the distribution can be interesting to be summarised in a single value. Thus, it is proposed a method that transforms the G_d^* matrix with S rows and 5 columns (SX5), to a single value $G^* \in [0,\ 10]$. For this purpose, it is proposed to apply two coefficients:

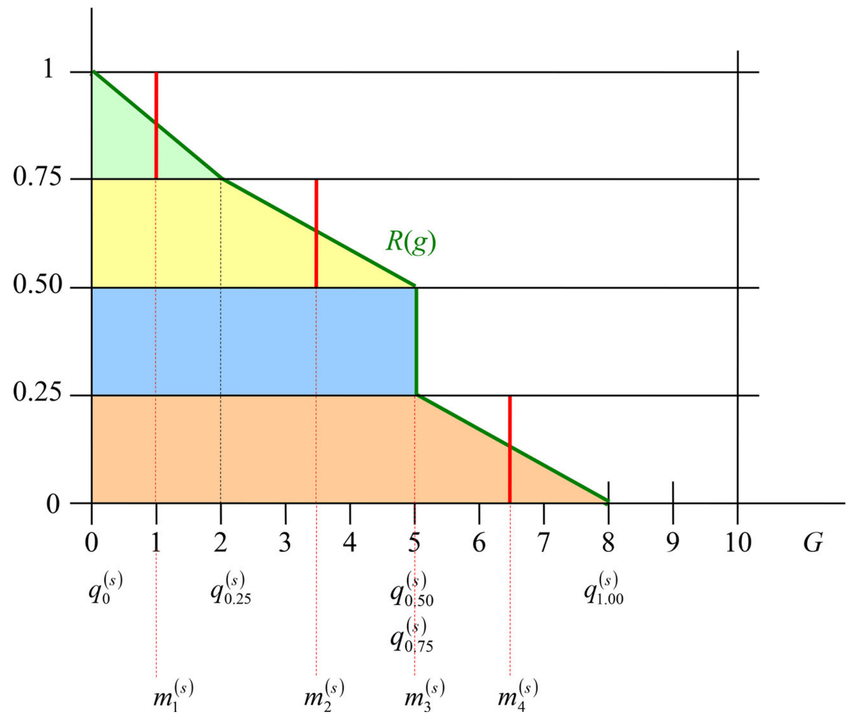

Figure 3. Function to determine the $G_r^{(s)}$ value.

Table 4. Weights $w_i^{(s)}$ depending on the values of the generic ratio r.

r	$w_1^{(s)}$	$w_2^{(s)}$	$w_3^{(s)}$	$w_4^{(s)}$
1	0.25	0.25	0.25	0.25
2	0.07	0.13	0.27	0.53
3	0.03	0.08	0.23	0.68
4	0.01	0.05	0.19	0.75

Table 5. Example of assigned weights to each building system.

Coefficient	System	Weight
$w^{(1)}$	Façades	0.15
$w^{(2)}$	Vertical structure	0.20
$w^{(3)}$	Horizontal structure	0.20
$w^{(4)}$	Roofs and inner courtyards	0.15
$w^{(5)}$	Interior building elements	0.05
$w^{(6)}$	Staircases	0.10
$w^{(7)}$	Sewer facilities	0.05
$w^{(8)}$	Other facilities	0.10

- $w^{(s)}$: coefficient for each of the S systems of the building, in order to give more weight to the most important systems;
- $w_{(\tilde{s})}$: coefficient for each of the S systems of the building, in order to give more weight to those systems that are in worse condition, which numerically means to give more weight to those highest values $G_{rw}^{(s)}$.

Consequently, it is proposed that G_w^* (G^* weighted) is obtained as follows:

$$G_w = \frac{\sum_{s=1}^{S} w^{(s)} \cdot G_{rw}^{(s)} \cdot w_{(\tilde{s})}}{\sum_{s=1}^{S} w^{(s)} \cdot w_{(\tilde{s})}} \tag{9}$$

Thus, through the proposed methodology WGB (Weighted Gravity Building), the numerical representation of the severity of a building passes from the matrix (SX5) of G_d^*, to a single scalar G_w^*. To provide flexibility to the methodology, it allows the technician to determine the relative weight $w^{(s)}$ that gives to each system, under the condition $\sum_{s=1}^{S} w^{(s)} = 1$. In order to propose a specific model to follow, it is considered appropriate the following assignment of weights that is presented in Table 5, for the division into 8 systems shown in Table 1. To obtain the different weights, hierarchical mathematical techniques are used (Saaty, 1988).

To obtain the weights $w_{(\tilde{s})}$, the triparameterized sigmoid function is proposed, shown in Figure 4, which gives more weight to those highest values $G_{rw}^{(s)}$. In order to define the triparameterized sigmoid function it is proposed the set of values $x_i = 4.5$; $y_i = 0.5$; $\alpha = 3$ (thus (4.5; 0.5; 3) in vector form). By applying this sigmoid, and under the condition $\sum_{s=1}^{S} w^{(s)} = 1$, it is obtained the following ratio of weights:

$$\begin{aligned} w_{(1)} = \; 0; w_{(2)} = \; 0.00; w_{(3)} = \; 0.03; w_{(4)} = \; 0.09; w_{(5)} \\ = \; 0.16; w_{(6)} = \; 0.22; w_{(7)} = \; 0.25; w_{(8)} = \; 0.25 \end{aligned} \tag{10}$$

It should be noted that the application of the proposed methodology by a technician is easy, because simply by determining the G_j severity (through DA method) and the S_j surfaces of different areas j, it is possible to obtain automatically the resulting severities of each system $G_{rw}^{(s)}$ and the resulting severity of the building, just using a spreadsheet. Likewise, by applying the proposed methodology to real cases of buildings, consistent results have been obtained, confirming the goodness of the proposed methodology.

4. Application to a real case

In this section, the proposed methodology is applied for calculating a real case of building. To obtain different values G_j

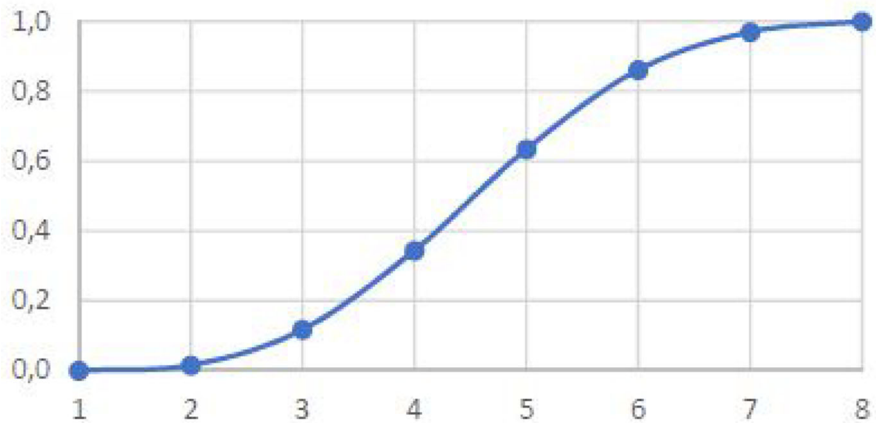

Figure 4. Example of sigmoid function.

is used, as proposed in Section 3, the direct assignment method (DA) based on the generic definitions of the proposed severity scale (from $G = 0$ to $G = 10$). The building for the practical application of the proposed methodology, located in the city of Barcelona, has been selected because of the following reasons:

- It has a constructive typology, characteristics and materials which are quite common in residential buildings.
- It is quite old (built in 1860), aspect that is considered positive, as there are more chances that there are deteriorations than in a new building. Likewise, buildings of this antiquity or higher are quite common in Spain.
- Much of the building is inhabited, aspect that is considered positive since it is common in residential buildings.
- It has varied deteriorations of varying severity and type, which is positive to achieve a more illustrative practical application of the proposed methodology.

Because of space limitaions, it is only detailed the calculation of one of the systems. The results of the other systems are presented directly, which in turn allows to calculate the total gravity of the building according to the proposed methodology.

4.1. System 1: Façades

4.1.1. Main façade

The first step is the delimitation of the different zones j with different gravities (different values G_j), as well as the direct assignment of the G_j value and the determination of the area A_j (in m^2) for each zone j. There are some notations in red and other in yellow for easy viewing, in case the reader has the document in black and white. As can be seen in Figure 5, in zone 1 the value $G_1 = 4$ has been determined by direct assignment (based on the definitions of the proposed scale) and the surface of this zone is $A_1 = 4.5\ m^2$. Similarly, in the zone 2 it is assigned $G_2 = 2$, and an area $A_2 = 0.3\ m^2$. The rest of the main façade (zone 3) is in good condition, therefore, its value is $G_3 = 0$, and the area of this zone is $A_3 = 62.4\ m^2$.

4.1.2. Rear façade

The same procedure as for the main façade is used, delimiting the different zones j with different severities (different values G_j) and the direct assignment of value G_j and determining the area A_j (in m^2) for each zone j. In this case comprises from zone 4 to zone 18 (it starts with zone 4 as it is considered together the whole façade system, including in this case the main façade and the rear façade). In this context, must be emphasized that most of the buildings have at least two façades (main and rear façades) (Figure 6).

Table 6 presents the set of values G_j and A_j obtained for the system 1 (facades, including therefore the values obtained for the main facade (zones 1 to 3) and for the rear façade (zones 4 to 18)). Similarly, it is included the weight w_j (surface or proportional part of the element j (Aj) respect to the total area (AT) of the considered system),as follows:

$$w_j = \frac{A_j}{A_T}, \text{ with } \sum_{j=1}^{n} w_j = 1 \tag{11}$$

being in this case $AT = 134.4\ m^2$.

Next, it is proceeded to cluster the zones with the same value G_j and sort them increasingly according to their corresponding values G_j (starting therefore since the lowest values $G_{j)}$. Also are included the weights w_j, the accumulated values of w_j (that it is denoted $W_{j)}$ are calculated, and it is calculated the corresponding components q_k (see Table 7).

Thus, in this case results the vector $G_d^{(1)} = (0, 0, 1, 3, 7)$. It can be said that, logically, the calculation could have been done separately for each façade, thus obtaining a vector for the main façade and another for the rear façade, if for example it was necessary to analyse separately both facades. Applying the same methodology, the vectors $G_d^{(s)}$ are obtained for the other systems of the building. Thus, the resulting vectors for these systems are included in Table 8.

Once obtained the eight vectors $G_d^{(s)}$ representing the distribution of the gravity of each system s, the distribution of gravity of the building G_d^* is determined by the Equation (8), explained in Section 3. Hence, in this case the matrix is:

Figure 5. Views of the main façade.

$$G_d^* = \begin{pmatrix} 0 & 0 & 1 & 3 & 7 \\ 1 & 1 & 1 & 2 & 4 \\ 0 & 2 & 4 & 6 & 8 \\ 1 & 2 & 2 & 4 & 5 \\ 0 & 2 & 2 & 3 & 10 \\ 1 & 2 & 2 & 3 & 10 \\ 1 & 1 & 3 & 4 & 7 \\ 1 & 1 & 2 & 4 & 6 \end{pmatrix}$$

4.2. Calculation of the resulting total severity of the building

As it has been seen, to calculate the resulting total gravity of the building G_w^* through the WGB (Weighted Gravity System) method is used the Equation (9), explained in Section 3:

$$G_w = \frac{\sum_{s=1}^{S} w^{(s)} \cdot G_{rw}^{(s)} \cdot w_{(\bar{s})}}{\sum_{s=1}^{S} w^{(s)} \cdot w_{(\bar{s})}} \qquad (9)$$

where $w_{(\bar{s})}$ are the weights derived from the respective sigmoid functions, given in Equation (10). Table 9 shows the values obtained by the WGB method, through the use of a spreadsheet in Excel. Next, an analysis of the influence of the r, x_i, y_i, α values is made, for obtaining the resulting gravities of the systems $G_{rw}^{(s)}$ and the gravity of the whole building G_w^*.

4.2.1. Influence of the parameter r

In Table 9 can be seen by comparing the analysis cases 2 and 5 (and similarly cases 4 and 6) that increasing the parameter r the resulting gravities of the systems $G_{rw}^{(s)}$ increases and

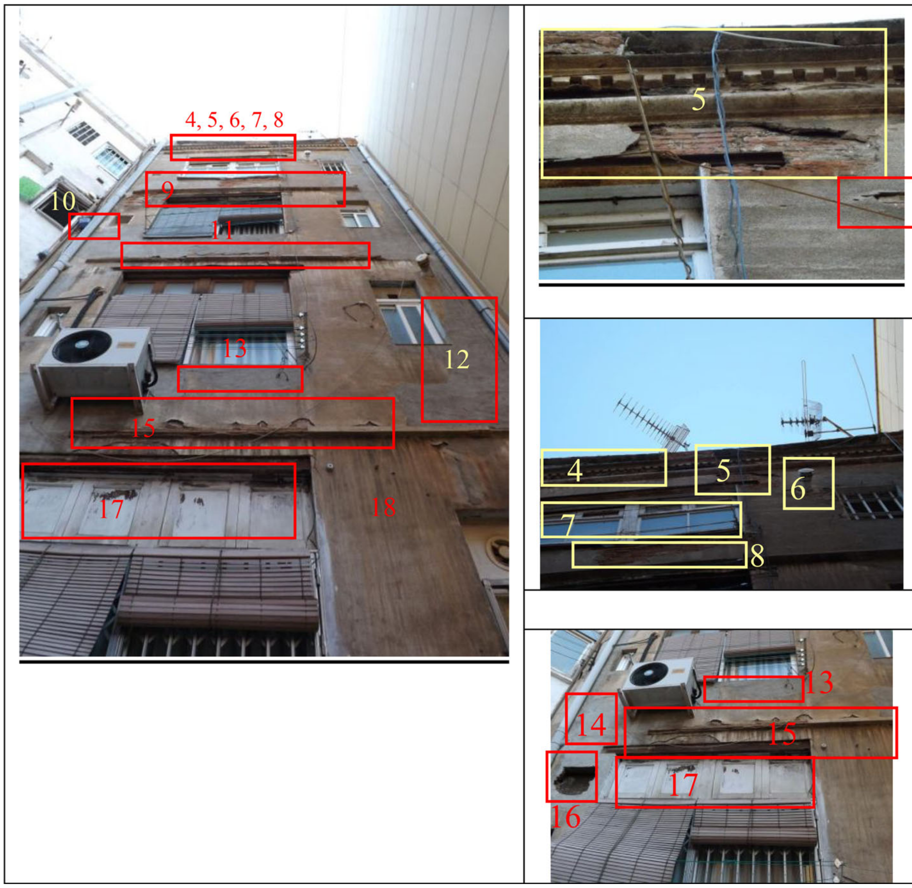

Figure 6. Views of the rear façade.

Table 6. Set of values G_j and A_j obtained for the system 1.

corresponds to the main façade (zones 1–3)

corresponds to the rear façade (zones 4–18)

zone	G_j	A_j	w_j	zone	G_j	A_j	w_j	zone	G_j	A_j	w_j
1	4	4.5	0.03	7	5	2.5	0.02	13	1	2.0	0.01
2	2	0.3	0.00	8	6	2.0	0.01	14	1	1.0	0.01
3	0	62.4	0.46	9	6	4.0	0.03	15	6	4.0	0.03
4	6	1.0	0.01	10	1	2.0	0.01	16	6	1.0	0.01
5	7	1.5	0.01	11	6	4.0	0.03	17	3	2.5	0.02
6	5	1.0	0.01	12	1	2.0	0.01	18	3	36.7	0.27

Table 7. Values q_k of the system 1.

System 1			
G_j	w_j	W_j	q_k
0	0.46	0.46	$q_0 = 0$
1	0.07	0.53	$q_{0.25} = 0$
2	0.00	0.52	$q_{0.50} = 1$
3	0.27	0.80	$q_{0.75} = 3$
4	0.03	0.83	
5	0.03	0.86	
6	0.13	0.99	
7	0.01	1.00	$q_{1.00} = 7$

therefore also the gravity of the whole building G_w^* increases, as can be observed from Table 9, comparing again the analysis cases 2 and 5 (and similarly cases 4 and 6). Increasing the parameter r physically means that more weight is given to those parts of the system in worse condition.

4.2.2. Influence of the parameter α

In Table 9, it can be seen that by increasing the parameter α (cases 1, 2 and 3), logically it does not affect the values $G_{rw}^{(s)}$, as the sigmoid function is used to obtain the weights $w_{(\tilde{s})}$, that are applied to the values $G_{rw}^{(s)}$ to calculate the value G_w^*. On the other hand can be seen in Table 9 (cases 1, 2 and 3) that the parameter α produces an increase of G_w^*, as increasing this parameter physically means that more relative importance is given to the systems in worse condition regard to the systems in better condition.

4.2.3. Influence of the parameter x_i

In Table 9 can be seen by comparing the analysis cases 2 and 4 (and similarly the cases 5 and 6) that by increasing the parameter x_i again does not affect the values $G_{rw}^{(s)}$, due to the same

Table 8. Values q_k of the systems 2 to 8.

System 2 Vertical structure				System 3 Horizontal structure				System 4 Roofs and inner courtyards				System 5 Interior building elements			
G_j	w_j	W_j	q_k	G_j	w_j	W_j	q_k	G_j	w_j	W_j	q_k	G_j	w_j	W_j	q_k
1	0.50	0.50	$q_0 = 1$	0	0.10	0.10	$q_0 = 0$	1	0.20	0.20	$q_0 = 1$	0	0.20	0.20	$q_0 = 0$
2	0.40	0.90	$q_{0.25} = 1$	2	0.30	0.40	$q_{0.25} = 2$	2	0.30	0.50	$q_{0.25} = 2$	2	0.40	0.60	$q_{0.25} = 2$
4	0.10	1.00	$q_{0.50} = 1$	4	0.20	0.60	$q_{0.50} = 4$	4	0.30	0.80	$q_{0.50} = 2$	3	0.20	0.80	$q_{0.50} = 2$
			$q_{0.75} = 2$				$q_{0.75} = 6$				$q_{0.75} = 4$				$q_{0.75} = 3$
			$q_{1.00} = 4$				$q_{1.00} = 8$				$q_{1.00} = 5$				$q_{1.00} = 10$
				6	0.20	0.80		5	0.20	1.00		6	0.18	0.98	
				7	0.10	0.90						10	0.02	1.00	
				8	0.10	1.00									
$G_d^{(2)} = (1, 1, 1, 2, 4)$				$G_d^{(3)} = (0, 2, 4, 6, 8)$				$G_d^{(4)} = (1, 2, 2, 4, 5)$				$G_d^{(5)} = (0, 2, 2, 3, 10)$			

System 6Staircases				System 7Sewer facilities				System 8Other facilities			
G_j	w_j	W_j	q_k	G_j	w_j	W_j	q_k	G_j	w_j	W_j	q_k
1	0.20	0.20	$q_0 = 1$	1	0.30	0.30	$q_0 = 1$	1	0.20	0.20	$q_0 = 1$
2	0.40	0.60	$q_{0.25} = 2$	3	0.30	0.60	$q_{0.25} = 1$	2	0.30	0.50	$q_{0.25} = 2$
3	0.20	0.80	$q_{0.50} = 2$	4	0.30	0.90	$q_{0.50} = 3$	3	0.20	0.70	$q_{0.50} = 2$
4	0.18	0.98	$q_{0.75} = 3$	7	0.10	1.00	$q_{0.75} = 4$	4	0.20	0.90	$q_{0.75} = 4$
10	0.03	1.00	$q_{1.00} = 10$				$q_{1.00} = 7$	6	0.10	1.00	$q_{1.00} = 6$
$G_d^{(6)} = (1, 2, 2, 3, 10)$				$G_d^{(7)} = (1, 1, 3, 4, 7)$				$G_d^{(8)} = (1, 2, 2, 4, 6)$			

Table 9. Total gravity of the building in the real case.

Model	Case	r	x_i	y_i	α	Total gravity of the building
WGB	1	3	4.5	0.5	2	5.85
	2				3	5.89
	3				4	5.90
	4		6.0		3	6.14
	5	4	4.5			6.06
	6		6.0			6.30

reason before indicated. On the other hand can be seen in Table 9 (comparing the preceding cases) that the parameter x_i produces an increase of G_w^*, as increasing this parameter produces an asymmetry of the sigmoid function to the right, which physically means that the number of systems in worse condition to which more relatively importance is given is smaller. It also means that the difference in relative importance is greater (higher weights $w_{(\bar{s})}$) for these systems in worse condition.

5. Conclusions

A severity scale of damage in buildings, of generalised and common use is needed in order to obtain a standardised method for deterioration index in buildings, where comparison between different countries and owners could be feasible. The main contribution of this paper is to propose a calculation method, in distribution and in scalar, to calculate severities of systems and of the entire building, easy to use and flexible, based on a proposed initial severity scale of damages in buildings, with 11 degrees of gravity (from 0 to 10). Some of the used mathematical techniques in the proposed methodology are the next: statistical quantiles, expectancy of a positive random variable X, hierarchical mathematical and triparameterized sigmoid function.

The obtained results are consistent when applied to real cases of buildings. It is important to highlight that this methodology can be applied to any existing scale of severity of damages in buildings. Hence, there have been developed useful tools in the context of buildings diagnosis with the next characteristics:

- They are understandable and easy to use.
- They are easy of being implemented.
- Consistent and interpretable results are obtained.
- There is low variability among technicians when using the scale.
- It is wide in scope (any kind of building, any geographic location).

This research is useful to be linked with other research on scales related with the deterioration index in buildings. On the one hand, research to calculate what is the optimal metric (number of degrees) for a scale of this scope (see Ruiz et al., 2019b). On the other hand, research to propose a methodology to calculate the degree of severity of a zone, based on physical parameters and mathematical equations (see Ruiz et al., 2019a). And these three research lines provide an integrated methodology to calculate the severity index in buildings.

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No potential conflict of interest was reported by the authors.

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