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How reliable are geometry-based building indices as thermal performance indicators?

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ABSTRACT

Architects and urban planners have been relying on geometry-based indices to design more energy efficient buildings for years. The advantage of such indices is their ease of use and capability to capture the relation of a few geometric variables with the building's performance. However, such relation is usually found using only a few simple building models and considering only a few climate regions. This paper presents the analysis of six geometry-based building indices to determine their adequacy in eight different climate regions in Europe. For each location, three residential building design programs were used as building specifications. Two algorithms were employed to randomly generate and assess the thermal performance of three sets of 500 alternative building models. The results show that geometry-based indices only correlate with the buildings' thermal performance according to specific climate regions and building design programs.

1. Introduction

Building performance indices have been used by architects, urban planners, and legislators as indicators to design more energy efficient buildings. The advantage of such indices is their ease of use and capability to capture the relation of a few geometric variables with the building's performance. Different indices may be used in different stages to complement each other and help in the decision-making process. Also, some are frequently defined as legal requirements by legislators. There are mainly three types of indices: shape-based, window-based, and what may be called as hybrid type. The shape-based indices are centered on the relation between the exterior surface area and the interior volume of the building [1–4]. They have been shown to be accurate in cold climates where the preservation of heat in the interior of the building is important [1,5]. Window-based indices, on the other hand, focus on the contribution of solar gains through the transparent envelope areas of the building [6–8]. Finally, the hybrid indices consist in combining several design variables, in addition to those mentioned above. These may be site related and consider physical properties of materials, climate data, solar irradiation and solar heat gains [9–11].

On one hand, the use of a shape-based index such as compactness may be very useful during the planning phase, helping to determine the precise needs of construction materials and thus its embodied energy [12]. However, when focusing on the presented question, the shape-based index may be criticized as it does not capture the specific morphology of a building's shape and distribution of the transparent components, nor does it take the building's orientation into account [2]. Certain authors refer that Shape Coefficient (C_f) does not consider the specificity of each climatic region, thus the index may fail in mild and sunny weather conditions, knowing that the transparent area of the building envelope has significant influence on heating or cooling demands [1,4,5].

In what concerns the window-based indices, studies show that their applicability helps to realize that windows size do not have a major influence on heating demand in cold climates [6] or on cooling demand in mild or hot climates [7,8] when using the most adequate glazing type for each case. This is an important issue, especially when balancing with visual comfort throughout daylight; although, openings represent one element within a complex set of variables, and it is not usual to base a building design solely on this parameter [13].

For these reasons, other methods were used as alternative approaches to geometry-based indices. Some methods look to combine some geometry-based indicators with materials physical properties, solar heat gains, solar irradiation, and site-related data [9,11]. Ekici and Aksoy [14] used neural networks to predict energy

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needs according to orientation, insulation thickness, and transparency ratio variables for three building samples with different form factors. Statistical analysis can be used to determine the relations between different building parameters and the amount of heating demand in residential for French climate [15] and Italian climate [16]. Steadman et al. [17] used a three-dimensional digital model of the city of London to measure the buildings' volume, exposed surface area, and plan depth to statistically compare with the consumption of electricity and gas at the urban level. Other approach is to use regression analysis [10,18] to identify a fitting curve between the annual energy use and some parameters that can be expressed in a single equation. The use of sensitivity analysis [19,20] allows testing the impact of different parameters value in the overall building performance. However, such approaches have the disadvantage of being overly sophisticated to be used in daily architectural practices.

The correlations found for those indices result from very controlled building models with specific characteristics, e.g. by keeping the same volume and window area, and merely altering the form, allows determining if there is any relation between building form and its energy consumption [9,10,14,15,18,19,21]. Those building models are very simple and disregard several aspects which may interfere in the results, such as having different thermal zones instead of a single zone, definition of their internal gains (occupancy, type of occupancy, artificial lighting, and equipment), and schedules of use. Such simplifications of the building models occur because in the early design stage, several decisions are not yet definitive. For instance, architects usually start by defining the overall shape and window areas according to the expected performance before determining the interior space configuration. However, this neglects specific requirements in each space (performance, functional, topological, and geometric) and how this can affect the envelope design; the window dimensions in one room depend on its function and occupancy, thus the overall window area in the building envelope results on the position of that room in the floor plan and how it relates to the remaining spaces of the design program. Such strict models are also very abstract and unrealistic in a real design scenario. i.e., in practice, an architect does not have to choose between a slim tower of 16 floors, a cubic building design, or other combinatorial variations of the same space unit [1,4].

The overall building form usually results from site, regulations, aesthetic preferences, and the design program. Therefore, in order for such building performance indices to be helpful in practice, they must assist the architect in comparing alternative designs within the same solution range, for instance to compare building tower designs with different forms. Thus, and according to the reference construction elements for the different countries that implemented the new European regulation [22], building performance indices are tested for their effectiveness in different climate regions and different building design programs. With this objective, six geometry-based building indices were selected for this study:

1. Shape Coefficient (C_f).
2. South Exposure Coefficient (C_s).
3. Relative Compactness (RC).
4. Window-to-Wall Ratio (WWR).
5. Window-to-Floor Ratio (WFR).
6. Window-to-Surface Ratio (WSR).

The Shape Coefficient (C_f) was used by Depecker et al. [1] and consists of the relation between the sum of all surface areas in contact with outside air (S) and the building's volume (V), defined in Eq. (1). This index represents the relation of area per unit volume, meaning that, for the same volume, the smaller the surface area, the less heat is transferred to the outside environment. This index may be obtained by inverting building's characteristic length (lc = $1/C_f$).

$$C_f = \frac{S}{V} \tag{1}$$

The C_f index has shown to have a good correlation with energy demand in cold climate regions of central Europe. However, C_f proved to be inadequate for mild and sunny climates [1,4], as the solar heat gains through the glazing areas in winter have a higher influence on the heat balance of the building [11]. For this reason Albatici and Passerini [4] proposed the South Exposure Coefficient (C_s). The C_s is the relation between the total south wall surface area $\left(S^S_{wall}\right)$ and the building's volume (V), according to Eq. (2). The authors argue that this index proved to be more adequate than C_f for an Italian climate due to the fact that buildings with wider south wall area and similar C_f are more exposed to solar radiation, thus reducing the heating requirements [4]. It is quite noticeable that in the work carried out by [4], the building models have the glazing areas mainly placed in the south wall.

$$C_s = \frac{S^S_{wall}}{V} \tag{2}$$

Relative Compactness (RC) consists of the volume (V) to surface area (S) of a building compared to a reference shape volume (V_r) and surface area (S_r), as defined in Eq. (3).

$$RC = \frac{V/S}{V_r/S_r} \tag{3}$$

However, buildings are usually a combination of parallelepiped shapes and for this reason a cube is used as the reference shape, as it is the most compact and orthogonal shape possible [2,9]. The advantage of such a building index is the fact that it is only shape-dependent and does not take into account the effect of size. Eq. (4) is used to determine the RC.

$$RC = \frac{6V^{2/3}}{S} \tag{4}$$

Window-to-Wall Ratio (WWR) consists in determining the relation between the total window surface area (S_{win}) and the total exterior wall surface area (S_{wall}, see Eq. (5)). The greater the windows surface area, for the same exterior wall surface area, the higher the gains through solar radiation and the higher the heat transfer with the exterior.

$$WWR = \frac{S_{win}}{S_{wall}} \tag{5}$$

Even though C_f, C_s, and RC take the building's volume into account, they do not consider the opening's characteristics. Contrary to these indices, WWR does not take the shape into consideration. The Window-to-Floor Ratio (WFR) allows establishing a relation between the total window surface area (S_{win}) and the total floor area (S_{floor}). By considering the height of each floor as being the same, WFR can be understood as an index that may relate to the building's volume. However, by only considering the window surface area, WFR does not capture the relation of heat transfer to the exterior of the building. Eq. (6) depicts the WFR index.

$$WFR = \frac{S_{win}}{S_{floor}} \tag{6}$$

Both WWR and WFR may be broken down into each orientation (North, East, South, and West).