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# Sensitivity analysis evaluating basic building geometry's effect on energy use

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ABSTRACT

Building form does influence energy consumption. Designing low-energy architecture to minimize energy consumption requires thoughtful articulation of the shape and form of a building. The Architect's decision-making for more energy efficient building form is often based on rules of thumb. Historically, the rule of thumb regarding passive solar building design suggests that form and orientation matter to overall energy performance. The question of how much impact does form have varies between project to project, due to climate, location, and building size. However, evaluation of energy performance specifically relating to building form is difficult to quantify because of the large solution space, but nonetheless important to understand.

The paper presents a methodology to evaluate building form to in order to compare energy consumption of geometric variations and material considerations through two types of sensitivity analyses. First, a review of related studies discussing energy and form are discussed, second the geometric methodology for vertical and horizontal proportion is described, and finally the linear screening local sensitivity index and a Morris global sensitivity results are reviewed. Findings compare geometric and material sensitivity, as well as the two different types of sensitivity analyses. Results indicate that both the vertical and horizontal geometric proportion is equally as sensitive as certain material aspects related to building energy use. Outcomes provide building designers clarity on the formal variations in the early design phase informing design decision-making.



## 1. Introduction

Reviewing recommendations in several design guides published for architects, such as Victor Olgyay [1] suggests, form does matter related to orientation and aspect ratio. Many subsequent passive solar projects completed thereafter adopt the suggestions for building orientation and form. The book Architect's Studio Companion by Allen [2] recommends orientation of building and glazing along an east west axis to maximize natural lighting and design with daylight. Similarly, the 2004 ASHRAE study by Ross [3], questions the energy performance of orientation related to overall energy performance. However, more recent guides identify the complexity of building form on energy performance. “Less compact forms increase a building's daylighting potential, but they also may magnify the influence of outdoor climate fluctuations. Greater surface-to-volume ratios increase conductive and convective heat transfer through the building envelope. Therefore, it is critical to assess the daylighting characteristics of the building form in combination with the heat transfer characteristics of the building envelope in order to optimize overall building energy performance.” [4]. Herein is the complex problem of balancing multiple variables of form, shape, volume, daylight, and envelope in the design of low-energy architecture.

Primary interest is how building form affects a buildings energy use, which precedes many mechanical systems and renewable energy considerations. One measure is form compactness as one energy reducing strategy [5,6]. The effect of compactness on energy savings varies depending on climate [7]. To measure the compactness of forms and maintain constant volume using surface area ratio is necessary. Analysis done by Gratia and Herde [5] shows a 18.6% heating load difference between the highest and lowest compactness ratio (1.24–0.84). However, their simulation was

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limited to heating loads only, not understanding cooling loads, which may be appropriate for buildings in Belgium, but is not transferable into other climatic zones. Expanding on this analysis, Straube [8] recommends the use of usable floor area to above-grade enclose area ratio, *F*/*E*; therefore, rewarding buildings with less floor-to-floor height. Comparing the studies [5–7,9] a small range of building form variation and compactness shows a limited range of variation produced from different forms.

Other studies investigating building form, suggests that form does matter to solar energy production [10–12]. For instance, Hachem et al., [10] looked at multi-family housing study shows the potential of roof areas to maximize renewable energy production. This study investigated various housing shapes and types simulating the total radiation (kWh/m$^2$). The type of simulation focusing on solar radiation limited larger results related to the variety of building forms and energy use. Kampf [11] suggests that building form optimized for different urban types and built volumes. However, solar radiation in dense environments can be limited [12]. A Scandinavian study [12] showed some forms are more significant than others in dense urban area. These papers highlight how in denser urban areas form and orientation effects energy use.

Ross [3], comparing 156 simulations of thirteen different building forms, four enclosure types and three window wall ratios (WWRs), and orientations concludes that neither a formal variation of a type, nor a re-orientation are crucial, and that WWR and enclosure performance are far more important. When combining choices of building shape with enclosure types and WWR, the energy-intensity of the higher performing building types dropped 60% over the energy-intensity of “market” types. The simulations evaluated small, medium, and large office buildings in Toronto from 12,000, 50,000, 160,000 sq. ft. respectively. The results range from an Energy Usage Intensity (EUI) of 158–315 kWh/m$^2$/yr. The author concluded that form alone has very little influence on the EUI of the types tested and that medium-sized buildings were most sensitive to plan form change. Also, that orientation has very little influence. Finally, that WWR was shown to produce the widest range of variation in EUI. This study while comprehensive only looked at set plan forms for different sizes, not variations within the shape types studied. Secondly, the geometric variations in building compactness and volume were not clearly articulated or controlled for, making the EUI comparison limited. Contrary to these findings, Pacheco et al. [13] in their review of literature on sustainable building design concluded that factors with the greatest repercussion on the final energy demand are building orientation, shape, and the ratio between the external building surface and building volume.

Since, BEM is used early and often [14,15], and can help designers make decisions for higher performing buildings. Clearly understanding the specific sensitivity of geometric variation of building shape is important. The paper explores this question by first explaining the methods and defining what aspects of building geometry are worthy of analysis. The geometric aspects outline the methods of producing variation for controlled comparison. Following this, using local sensitivity and global sensitivity analyses can visibly provide designers with important information for decision-making.

## 2. Methods

In addition to those studies reviewed previously, methods involved in more in-depth investigations of building geometry and energy use looked at a wider range of geometric principles governing the shape [16–18]. The range of shape exploration each of these studies incorporates is a genetic algorithm in their methodology to evaluate energy performance across a range of geometric complexity. Similar to these studies and others using algorithms and simulation [19], this project utilized genetic algorithms to produce a wide range of shape variations based on proportional parametric relationships to maintain building volume. The sensitivity analysis completed uses the results of a whole Building Energy Model (BEM) simulating energy performance for these shape variations. The study elaborates on a geometric methodology to maintain building volume when evaluating vertical and horizontal proportional relationships to compare building geometry to material considerations in the sensitivity analyses (see Tables 2 and 3).

**Table 1**
Baseline building assumptions used in whole-building energy model.

| Default settings | |
|---|---|
| Window | U:0.38 |
| Wall | R: 11.4 |
| Roof insulation | R: 32 |
| VT | 0.90 |
| SHGC | 0.44 |
| Heating St. Pt. | 21.66 °C |
| Cooling St. Pt. | 24.44 °C |

Establishing the simulation involves defining a baseline house for consistent BEM evaluation of the results. Residential sizes of 1600, 2400, 3200 sq. ft. were evaluated, settling on 230.4 m$^2$ (2400 sq. ft.) for the subsequent stacking and sensitivity analysis. The limited building size of 230.4 m$^2$ is also the average size of a U.S. house in 2010. The sensitivity analysis also uses the 230.4 m$^2$ (2400 sq. ft.) setting a reference point of departure at an orientation of 90°, aspect ratio of 2.56, stacking level 1 and the materials according to the Building America (BA) benchmark [20] outlined in Table 1.

Considering the dimensional constraints of the geometry is critical to setting an effective standard for the following sensitivity analyses. For example, 3.15 m (10.36 ft) is hardly acceptable as the width of a residential unit. Therefore, using a 2.56 aspect ratio and a baseline house with a footprint of 230.4 m$^2$ keeps the formal variation within real buildable sizes. The residential type of building used eliminates the large demands of lighting, daylight, natural ventilation, and more complex mechanical systems from consideration allowing evaluation of the building form. These factors can have a significant impact on a buildings energy performance, however, the paper is concerned with simple single zone analyses to highlight the role geometry has on energy performance using sensitivity analysis.

### 2.1. Geometry theory and definition

A key factor in considering geometry is constraining the buildings overall volume and surface area related to its shape. Wide

**Table 2**
Local sensitivity index variables and ranges.

| Variable | Range |
|---|---|
| *Geometric* | |
| Stacking | 1 to 4 levels |
| Orientation | 0 to 135 rotation |
| Eave | 0 to 2 m |
| Aspect ratio | 4:20 to 4:4 (0.2–1) |
| *Material* | |
| Wall R-value | 11.4 to 30 |
| Roof insulation | 30 to 60 R-value |
| Window wall ratio (WWR) | 0.1 to 0.2 |
| Solar heat gain coefficient (SHGC) | 0.24 to 0.64 |
| U value of glazing | 0.18 to 0.68 |