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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

Table 3
Global sensitivity analysis variables and ranges.

Variable	Range
Geometric	
Stacking	1.0, 2.0, 3.0, 4.0
Orientation	0.0, 120.0, 240.0, 360.0
Eave	0.0, 0.66, 1.33, 2.0
Aspect ratio	0.2, 1.8, 3.4, 5.0
Material	
Wall R-value	10.0, 16.66, 23.33, 30.0
Roof insulation	15.0, 30.0, 45.0, 60.0
Window wall ratio (WWR)	0.10, 0.13, 0.16, 0.20
Solar heat gain coefficient (SHGC)	0.24, 0.40, 0.57, 0.74
U value of glazing	0.18, 0.34, 0.51, 0.68

swings in volume would not allow accurate comparison of results due to the internal zones evaluated with the BEM simulations. More volume equals more heating and cooling loads. Additionally, drastically increasing the surface area unrelated to the internal volume could create additional unpredictable results. The following two sections describe these considerations to maintain volume while evaluating variations in the horizontal and vertical proportions, here on referred to as aspect ratio and stacking, of a building form with BEM.

2.1.1. *Aspect ratio with roof variability*

Initially to determine maintenance of volume within changing floor plan shapes of a building geometry a square mass floor plan 30.48 m × 30.48 m × 9.14 m (100′ × 100′ × 30′) was given 20 different roof types. Roof variation benefits renewable energy production [10] within differing plan shapes. The set of 20 iterations tested variation of aspect ratios across different orientations. The roofs were added in ways that maintained volume of the space so that the amount of conditioned space had limited influence on annual energy use. For example, when tilting the roof for iteration two, pivoting the roof face from the center ensures that equal volumes are respectively added or subtracted from opposite sides. For some of the curved roofs where there was not mathematical means to maintain volume, the roof section was modeled, volume calculated and then added to a square base with the corresponding volume subtracted so that the total is still maintained. In order to maintain aspect ratio and volume, there were some differences in surface area were accepted.

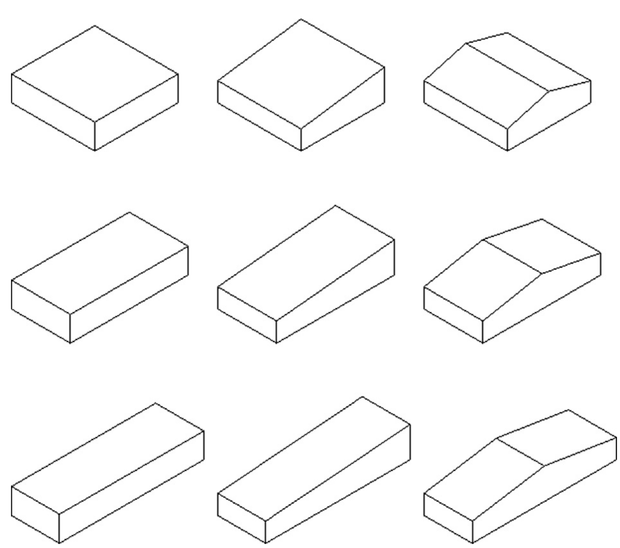

Fig. 1. Comparison of aspect ratio of various roof forms, comparing the original 1:1 (top) to 2:1 and 3:1 (bottom) while maintaining volume.

In addition to running the iterations at different orientations (multiples of 45°), each iteration was run through the set of orientations with aspect ratios of 2:1 and 3:1. To change the aspect ratio while maintaining volume, the x and y dimensions were scaled by reciprocals. For example, if the form is scaled one direction by 2 and the other by 1/2, you would maintain volume ((100*2/1)*(100*1/2) = 100*100), and the aspect ratio would be 4:1 ((100* 2/1) : (100*1/2) = 200 : 50 = 4 : 1). So in order to get aspect ratios of 2:1 and 3:1, this method was used with the reciprocal sets of $\sqrt{2}$ and $1/\sqrt{2}$ and $\sqrt{3}$ and $1/\sqrt{3}$ respectively. Equation listed below:

$$\left(\frac{100^*\sqrt{2}}{1}\right):\left(\frac{100^*1}{\sqrt{2}}\right)=\left(100^*\sqrt{2}^*\sqrt{2}\right):(100^*1^*1)$$
$$=(100^*2):(100)=2:1.$$

This method assigns each iteration a set of aspect ratios of 1:1, 2:1, and 3:1 all while maintaining internal volume (Fig. 1). Changing the aspect ratio to maintain volume minimizes increases in the surface area and therefore controls for increases in internal heating and cooling loads. Initial results showed no different between the roof variations, consequently roof differences were eliminated in the latter residential building analyses.

2.1.2. *Stacking*

2.1.2.1. Maintaining consistent volume. Shown in Fig. 2 is the relationship of the four boxes each of which has a width (w), length (l), and height (h). The ratio (R) is kept constant to maintain internal volume of the form, for now ($R = l/w$). For each of these boxes, the footprint area (A) will get half in size ($A_i = (A_{i+1}) * 2$) while the height becomes double ($h_i * 2 = h_{i+1}$). This is the stacking effect. The volume (V) is constant as follows:

$$V = a^*l^*h \quad \text{or} \quad V = (w^*l)^*h \quad V = A^*h$$

$$V_i = h_i^*(A_i) \quad V_{i+1} = h_{i+1}^*(A_{i+1}) \quad V_{i+1} = 2h_i^*\left(\frac{A_i}{2}\right) \quad V_i = V_{i+1}$$

Therefore, the volume is constant. However, the same is not true for the surface of box (SoB) or the surface of the walls (SoW). We also know SoB is the SoW plus the roof and the floor (2 * A) or SoB = SoW + 2 A.

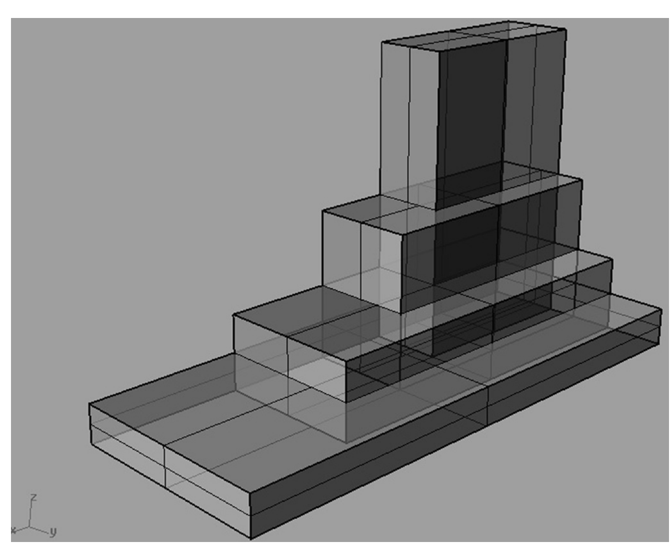

Fig. 2. Relationship of four boxes with equal volume.

With mathematical calculations, it is possible to define the rate at which SOW grows. If we show this growth as $\mathrm{SoW}_i - \mathrm{SoW}_{i+1}$, then we can say:

$$\mathrm{SoW}_{i+1} - \mathrm{SoW}_i = h_{i+1} * \left(1+R\right) * \left(w_{i+1}\right) * \left(1-\sqrt{2}\right)$$

Or

$$\mathrm{SoW}_i - \mathrm{SoW}_{i+1} = \left(\sqrt{2}-1\right) * h_{i+1}(w_{i+1} + l_{i+1})$$

To simplify this formula that shows the rate for the growth of the surface of the wall (SOW), called K and shown like this: $K = (\sqrt{2}-1) * (w+l) * h$.

2.2. Sensitivity methods

Following the sensitivity analyses [21–23] outlining the Morris method to evaluate building design variables, the sensitivity method the research relies on is Heiselberg et al. [21]. Their study concluded, "that a sensitivity analysis in the early stages of the design process can give important information about which design parameters to focus on in the next phases of the design as well as information about the unimportant design parameters that only will have a minor impact on building performance. The sensitivity analysis will improve the efficiency of the design process and be very useful in an optimization of building performance." Using sensitivity analysis early on can aid designers in establishing a goal-setting energy model based on design variables. This paper argues that aiding early design decisions is possible using a pre-design local sensitivity index and further expanded later during design optimization using a set design variables from a Morris Global Sensitivity Analysis (GSA).

In addition to expanded decision-making in building design using sensitivity analysis incorporates more detailed variables. The second agenda here is a need to demonstrate the impact of geometric variables along with the standard material and system building properties. To outline these differences and their performance ranges Section 3.2 describes a series of sensitivity charts [23] and compares a local sensitivity index with a GSA [21].

A reference study [24] produced by Autodesk for their design sensitivity analysis using Green Building Studio in Revit reports use of 40 different variables in their simulation. The number of variables evaluated can influence the accuracy due to the linear nature of the analysis. In some cases the simple high/low two variable range establishes the initial sensitivity as a linear function. This simplicity could limit defining a reasonable design range, which is critical to decision-making based on the analysis. In theory, one could create un-accurate sensitivity by choosing a range of widely different inputs therefore creating a sensitivity that does not reflect reality. Understanding and specifying a clear range for each variable is an important first step.

Building energy modelers commonly use sensitivity indices. For example, New Building Institute's (NBI) white paper [23] outlines a sensitivity analysis method for commercial buildings. Their study identifies a range of variables to consider. The graphs indices reported are helpful in identifying an individual design elements sole impact on energy performance on a design, not considering any other factors. However, this is a limitation as well. A building is a complex system of many interconnected and inter-related parts and only looking at one excludes the consideration of how it relates to the others. In the GSA, the analytical methods overcome this singular evaluative priority (in this case using the Morris method).

The range of sensitivity for each variable is described in a linear equation based on Lam and Hui [22] and the "sensitivity index" (SI) by Heiselberg et al. [21].

$$\mathrm{SI} = \frac{E\max - E\min}{E\max} 100\% \tag{1}$$

Here, equation (1) Emax and Emin represent the maximum and minimum design parameter variable range. Not all design parameters are worth including in a more rigorous sensitivity analysis because they may not vary significantly enough to have an impact. Therefore, exclusion of these variables from further analysis benefits the analysis. For instance, roof variations discussed previously and higher stacking ranges beyond a threshold of four.

Establishing a variable range tied to a baseline aids in identifying a reasonable performance target. In the local sensitivity index there are 120 different variables used for simulation to produce a more accurate range of sensitivity. Consequently, identified in Table 2 are the variables evaluated and their performance range used for the local sensibility index. Additionally, they are organized into those variables that are material and those that are geometric, omitting items unrelated to major architectural design considerations such as mechanical and electrical systems. The variables used are from a literature review completed previously on early design elements evaluated with BEM [15] and narrowed from initial screening to eliminate variables that were negligible to the sensitivity. An aspect of the study that differentiated from the baseline house was elimination of windows for the aspect ratio and stacking simulations. This occurred within just the geometric analysis, not the SI or GSA charts. Eliminating windows allows understanding only specific geometry factors and their related energy performance.

Based on these variables and ranges, simulations of each using a BEM generate results describing the performance range. Presentation of the results in the following results section is completed through the representation of the local SI both using and not using an established a baseline. For the graphical presentation of the SI the baseline house remains constant throughout all the variations

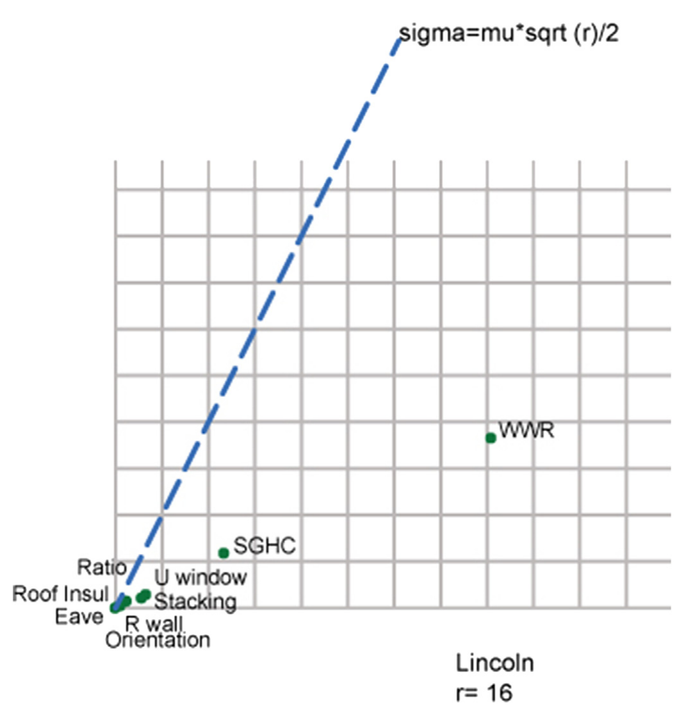

Fig. 3. Morris charts for sixteen ($r = 16$) iterations.

of the sensitivity charts. Therefore, one can compare which variable might affect gains or losses of energy. Representing the baseline house information in a bar chart using a reference line divides the energy values. In case of the SI, this reference line breaks the values into those, which decrease energy (green) and increase energy (red) in the chart.

Finally, to investigate the correlation between variables a GSA is required. The local SI merely identifies the individual impact of one variable on a building's energy performance. Using the global sensitivity the relationship of the one variable to all others is possible. As a non-linear function, the random inter-relation of a variable is understood based on the range of the others. Therefore, aiding design decision-making by demonstrating the impact of a single variable in relationship to the building's energy performance based on the other variables. Distinct from the local SI, which only describes the range of the one variable, the global sensitivity is effective at demonstrating how the variables interact with each other.

The initial SI screening influenced the parameters used in the Global sensitivity. The information obtained from the local sensitivity test (Indices) or from general BEM studies aided in narrowing down the number of parameters to those having the most impact. This process screens the variables and ranges leading to advancing only a few considered the most important. In this case, the study includes nine (9) variables. The next step defines the extreme values and each step of difference for the variables. In the script constructed for analysis, it is necessary to decide whether to use equal steps (levels) for the entire range of variables or if want differentiated steps as used in the ranges described Table 3. In the current study, four different steps were defined for each variable, largely based upon the orientation variable in order to include 45-degree rotations instead of the abrupt 90° ones.

The inputs into the analysis script were written to account for each variables range; the first value is the lower extent, then respectively: upper extent, default value, step size, and if a different level for the variable is done (note that this value is 0 for ever object other than orientation which demands 9 levels). Next, creating random vectors produces the test results corresponding to those vectors which changes one variable at a time to get the sigma and mu (μ) values. Based on the number of iterations creating Morris charts completes the GSA. Since the basic GSA formula relates to the r (iteration), increasing r produces different charts. Based on the sensitivity analysis an importance factor (μ) is determined for each variable.

Results of the analysis produce Morris charts, Fig. 3, the steep slope of the diagonal line changes based on the square root of the iteration. Additionally, highlighted in Section 3.2 is the ranking of the sensitivity results for the variables according to their importance (μ).

At this level and based on all the information that gathered the global sensitivity and all the linear or non-linear effects of the parameters are represented. The distance between each point and the dashed line shows how it operates; i.e., the further they are from the diagonal line the more independent (linear) the parameter is and vice versa.

3. Results

3.1. Geometric evaluation results

The geometry investigation evaluates two specific aspects of building form. First, the horizontal proportions of a residential footprint defined as the aspect ratio. Second, the analysis of stacking or vertical proportion of a building form. Evaluating each in isolation first helps to understand these variables design implication on energy performance. Consideration of common rotational impacts, building orientation, on energy performance is included. Each example has omitted windows in their initial evaluations to

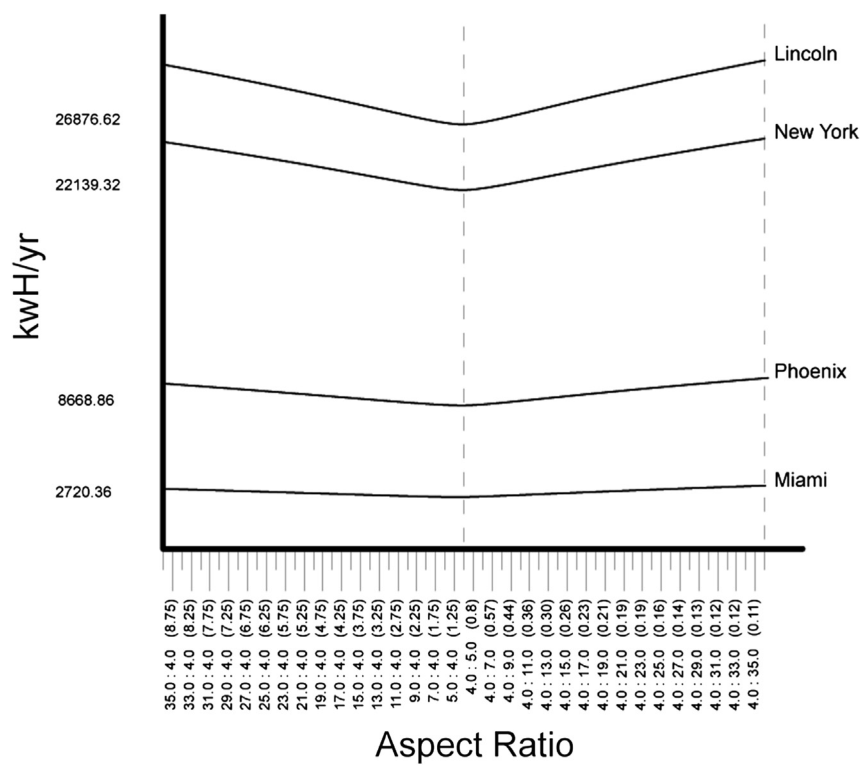

Fig. 4. Aspect ratio analyses.

highlight purely the geometric variables. Concluding the individual assessment is an evaluation of both aspect ratio and stacking. Following this section is the sensitivity analyses of these geometric variables along with typical material considerations of the building envelope.

3.1.1. Aspect ratio

The aspect ratio of a building's form relates the proportion of the length and width as a numerical expression. For example, 1:1; 4:4 the equivalent of one, would have the same length and width ratio, whereas 4:9 the equivalent of 0.44 would have a length of 4/9 and a width of 9/4. Factoring this into the analysis first was done on larger plan forms described previously, and then small residential sized forms comparing the change in kWh/yr energy impacts shown in Fig. 4. The material properties remained constant throughout the simulation.

The results from initial simulations of building aspect ratio suggest that the roof variations themselves had little impact on performance except in the way that they change surface area. While the difference in annual energy costs between the variations (at 1:1) reached 7%, this correlates with a reduced or increased wall surface area - because the footprint and volume where kept the same, the roof variations meant a change in surface area. The iterations with less surface area, and especially less wall surface area (due to being less insulated than the roof surfaces), expectedly performed better.

Orientation also had little impact on the 1:1 aspect ratio iterations, reaching over 0.1% difference only twice (and both instances were curved roof iterations which exhibited unexpected results as will be mentioned later). Increasing the aspect ratio to 2:1 and 3:1 saw a larger but still small impact from orientation, the highest among the non-curved iterations at just over 0.3%. The performance difference from orientation for the 2:1 and 3:1 iterations corresponded with the preference of an East–West axis (over North-South) for rectangular massing. The east and west walls receive more thermal energy from the lower morning and evening sun, while south facing walls receive less due to the midday sun's sharp angle, thus increasing southern wall exposure while reducing east and west lowers cooling loads (not considering glazing).

In conclusion, the roof variations and their orientations had a small/negligible impact on performance (except through increasing or reducing surface area, especially that of the walls). While, the difference between the best and worst iterations at 1:1 reached ~7%, this correlates with a reduced wall surface area (because the walls are less insulated than the roof, a reduction in their area had a bigger impact on performance).

3.1.2. Stacking results

Focusing on stacking reviewing the results reveals by increasing the stacking levels, stacking level one decreasing at level two then increasing for each subsequent level. Therefore, the optimal stacking level across locations is level two. Also referring to Fig. 5 both Lincoln and NY have the same optimal stacking level two and this supports the previous findings. The difference, however, is that in Fig. 4 the best ratio is 4:4 (both for Lincoln and NY) while the sensitivity base-line used 2.56. Therefore, optimal stacking depends on the ratio and location used discussed next.

3.1.3. Comparing aspect ratio and stacking results

Evaluating building form as reviewed earlier has many caveats related to how one defines the shape, volume and overall form of the building. To further investigate the relations between the aspect ratio and the stacking level simulations were done for each ratio step for each different stacking level. The chart in Fig. 6 demonstrates the results.

In that chart, all the values on the same dashed line have the same ratio, while the ratio increases along the x-axis. The other axis shows the loads (or source energy values). Each color represents a unique stacking level. Focusing on the loads, stacking level 1 is the optimal at the beginning (also pay attention that because the ratio is not logical and the east-west façade is too big the load is also the maximum at the very beginning) then at about the ratio of 0.5 the values become equal. From this point until the ratio of 2.1 the stacking level 2 is the optimal. But for larger values of the ratio the stacking level one returns to top. Again, the best case among all the illustrated choices (where the energy consumption is minimal) happens at about the stacking level 2 and the ratio of 1. This point is highlighted by a horizontal and a vertical dashed-dot line.

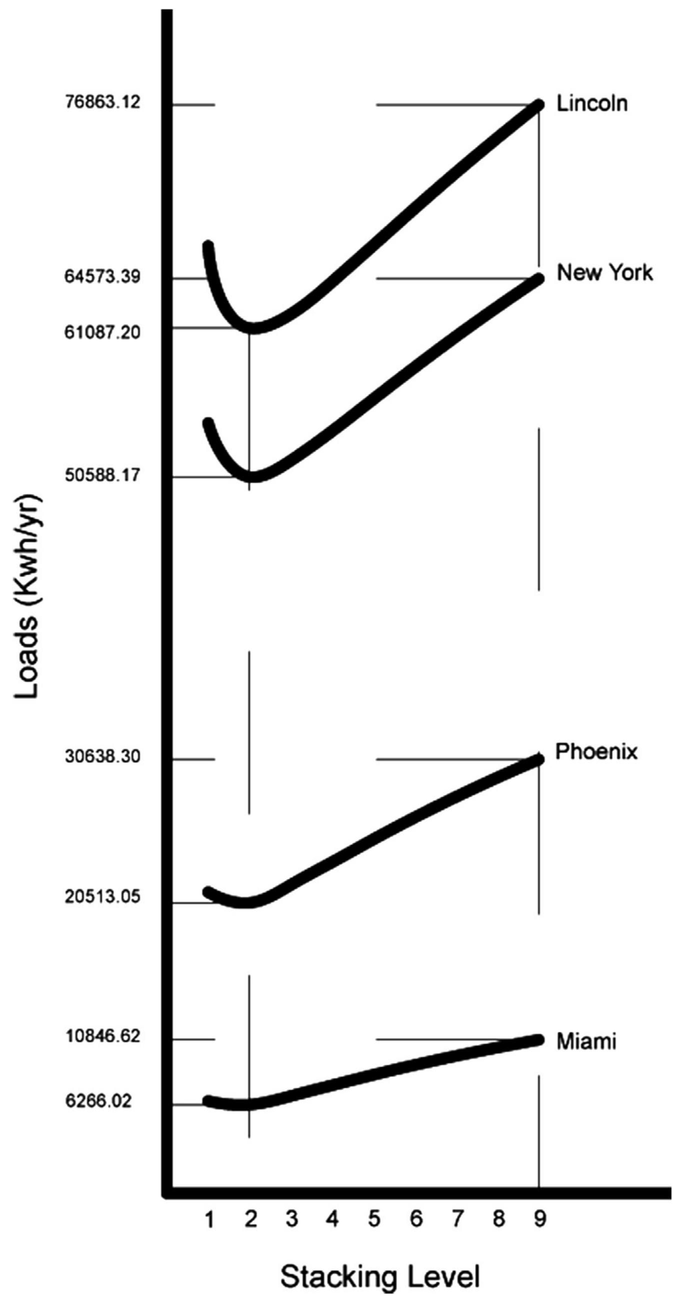

Fig. 5. Stacking effect shown for four different locations.

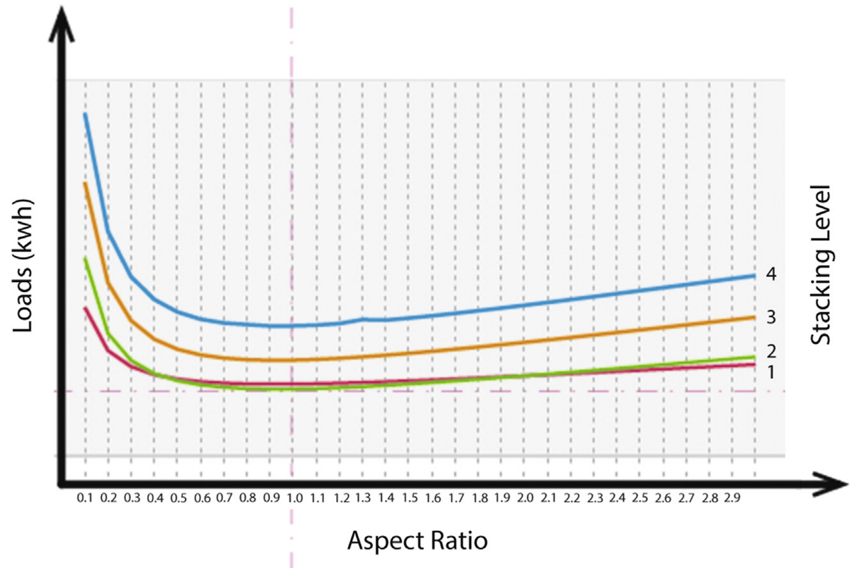

Fig. 6. Aspect ratio and stacking results from dual variable simulation.

3.2. Sensitivity results

Beginning with an existing design, the sensitivity chart may be helpful however, it would not deliver the optimal case. This is because the sensitivity works in a linear way: in a snapshot, where we arrest the variations of all factors but one and then go to the next. It is highly improbable to reach the optimal in this strategy. Additionally, using a base-line approach implies that there is already a design (post design optimization), but helps establish which variables to study further with a global sensitivity test. Therefore, completing a pre-design analysis using the global sensitivity analysis proposed by Heiselberg et al. [21], has potential

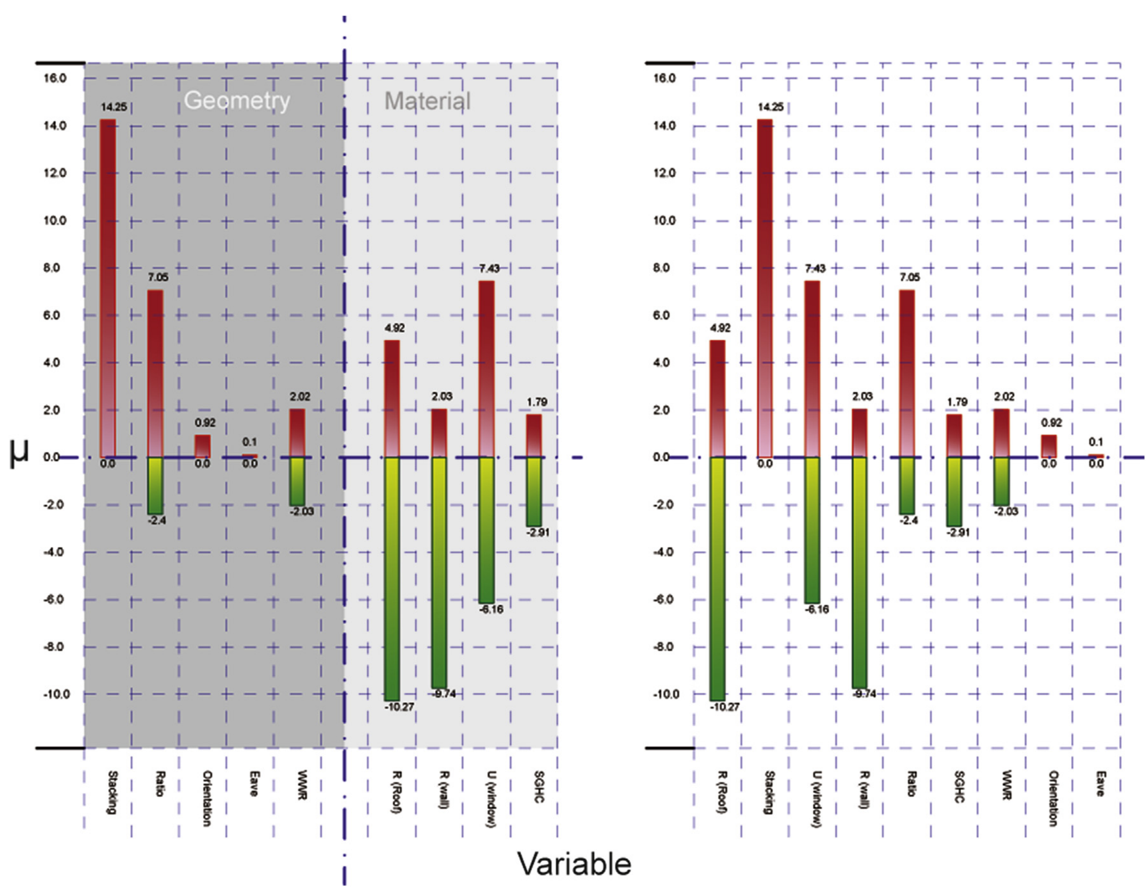

Fig. 7. Local sensitivity bar chart for **Lincoln, NE** showing grouped vs. ordered organization.

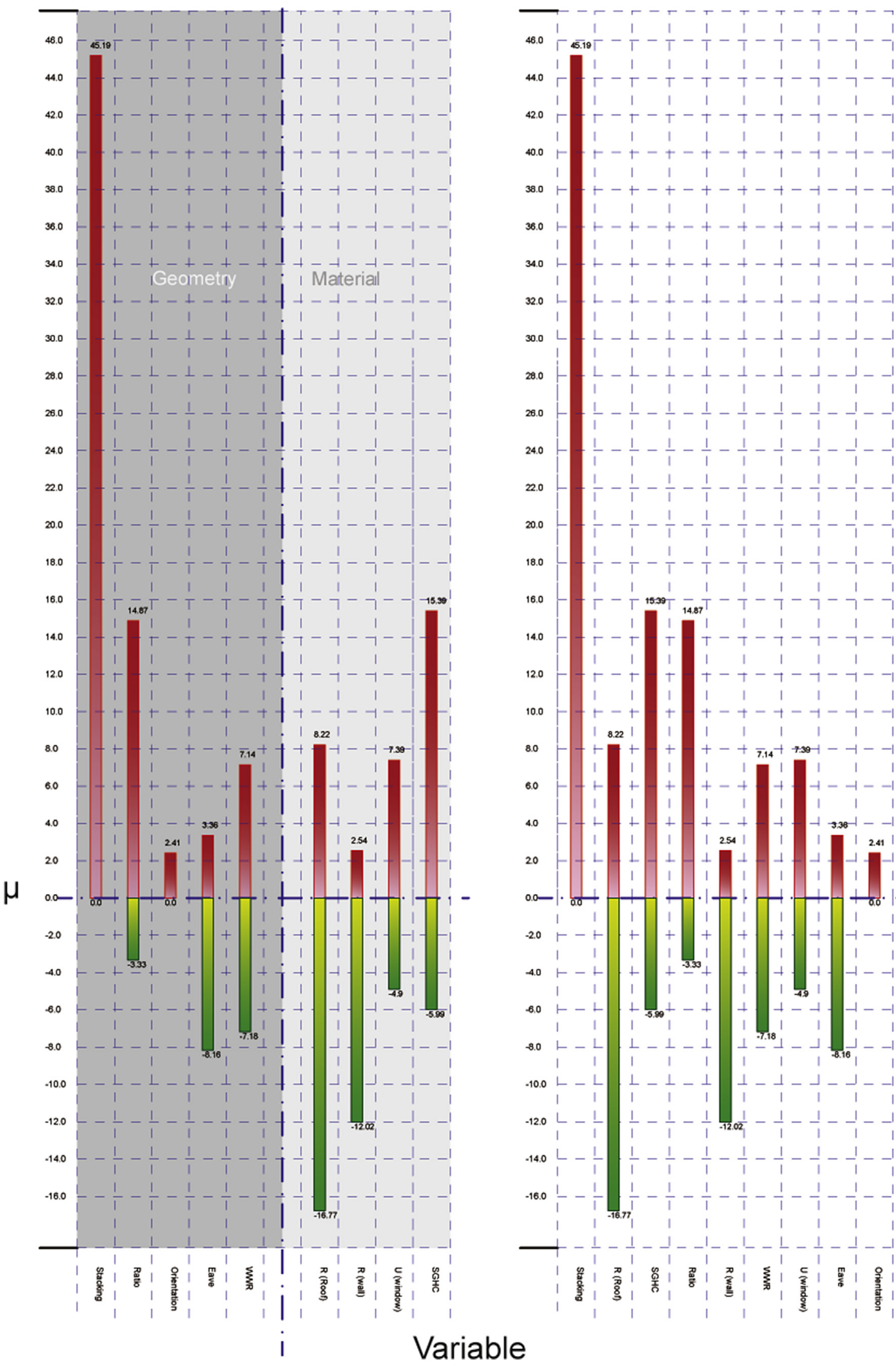

Fig. 8. Local sensitivity bar chart for **New York, NY** showing grouped vs. ordered organization.

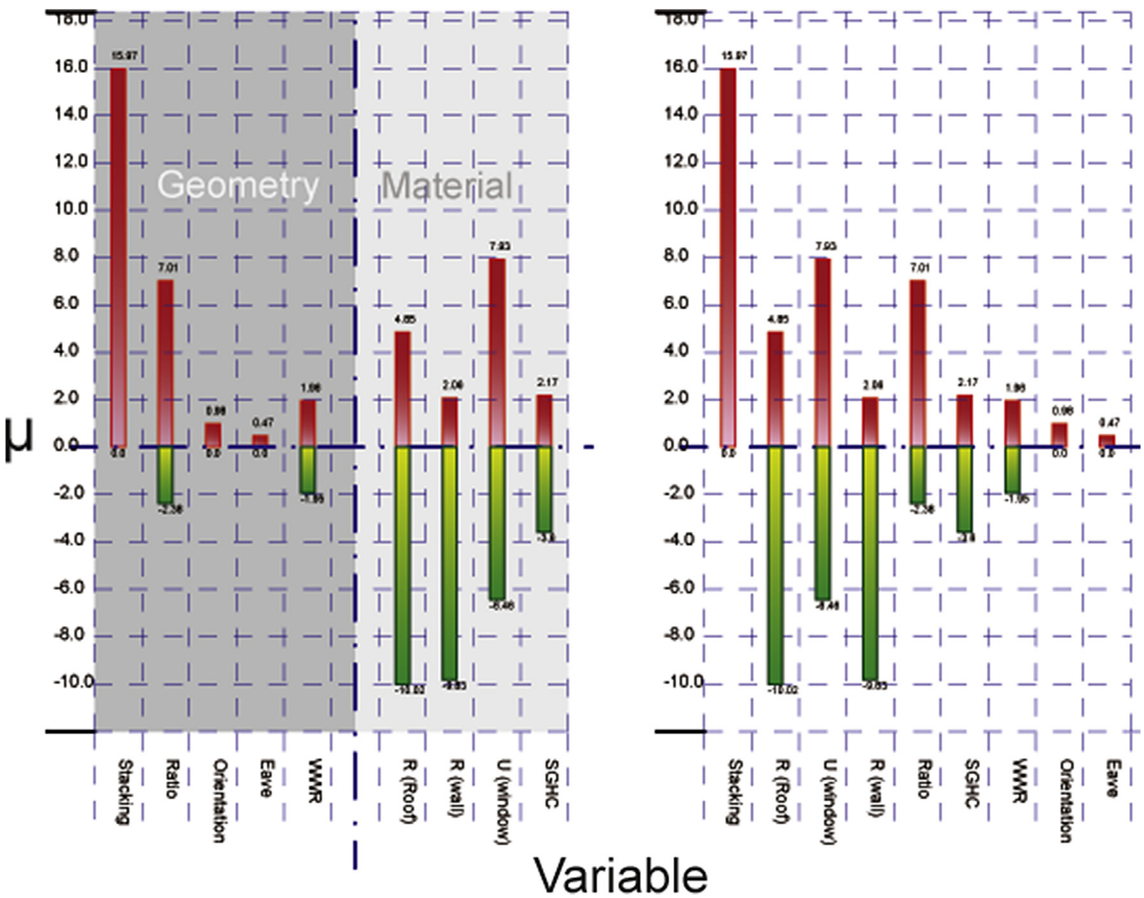

Fig. 9. Local sensitivity bar chart for **Miami, FL** showing grouped vs. ordered organization.

to produce a range of variables earlier and having more impact earlier in design.

Sensitivity charts, Figs. 7–10, define the SI of those variables, along the *x*-axis, having the most significant impact by their importance factor, shown along the *y* axis. These figures use a reference line of the Using a baseline allows decision-making using SI as a pre-design tool to test the geometric and material properties and the corresponding response from a specific location and climate. Additionally, sensitivity analysis may follow a conceptual design where actually dealing with a sketch and it is valuable to find out the crucial parameters that effect the energy consumption more than others. In these cases, designers may deal with decision-making processes in terms of material selection or secondary geometrical modifications. Four U.S. locations in differing climate zones added to the sensitivity analysis reported in the subsequent figures and tables presenting two charts side by side of the same variables grouped and ordered.

In either case however the parameters decided upon for the analysis and the sensitivity approach are both subjective and depend on the design objectives. In other words the design of the sensitivity analysis is done alongside the design the building. Hence, there is a need for customizable analyzers as part of any local or global sensitivity that are project specific.

Described in the following SI Tables 4–7 and GSA Tables 8–11 is the energy impact of geometric and material design elements in residential architecture. Ranking of each value in the table is according to the importance factor from most important to least for each of the four locations. Each location has two tables, the first is the local SI and the second is the GSA. Unique in both analyses is the addition of geometric variables of aspect ratio and stacking described in Section 2.

Weighing the inter-relationship between the design elements included in the analysis as GSA prioritizes each element not by how sensitive it is in itself, but by how sensitive it is in relationship to all the others analyzed (Tables 8–11). Therefore, comparing the local and global tables it is rather clear that the ranking of the WWR changes significantly. Meaning that the amount of glazing is the most interconnected element analyzed. A change in any of the others can therefore have an impact on the WWR, however not the inverse. Along these lines, the lower ranking items work more closely together rather than individually, as is the case for the WWR.

The GSA is a measure of how sensitive the particular design elements are in relationship to all the others. A high number therefore suggests the effective strength the other elements have on that design element. Alternatively, in the local sensitivity indices the importance factor identifies how much impact a particular design variable is in isolation. A higher importance therefore suggests that under the specific conditions defined this element has a more significant range of variation and effect on energy performance. Based on both the GSA and local sensitivity designers can select either individual design variables or a group for further investigation.

4. Discussion

Energy performance evaluation of building form is important in decision-making by Architects and Engineers to achieve high

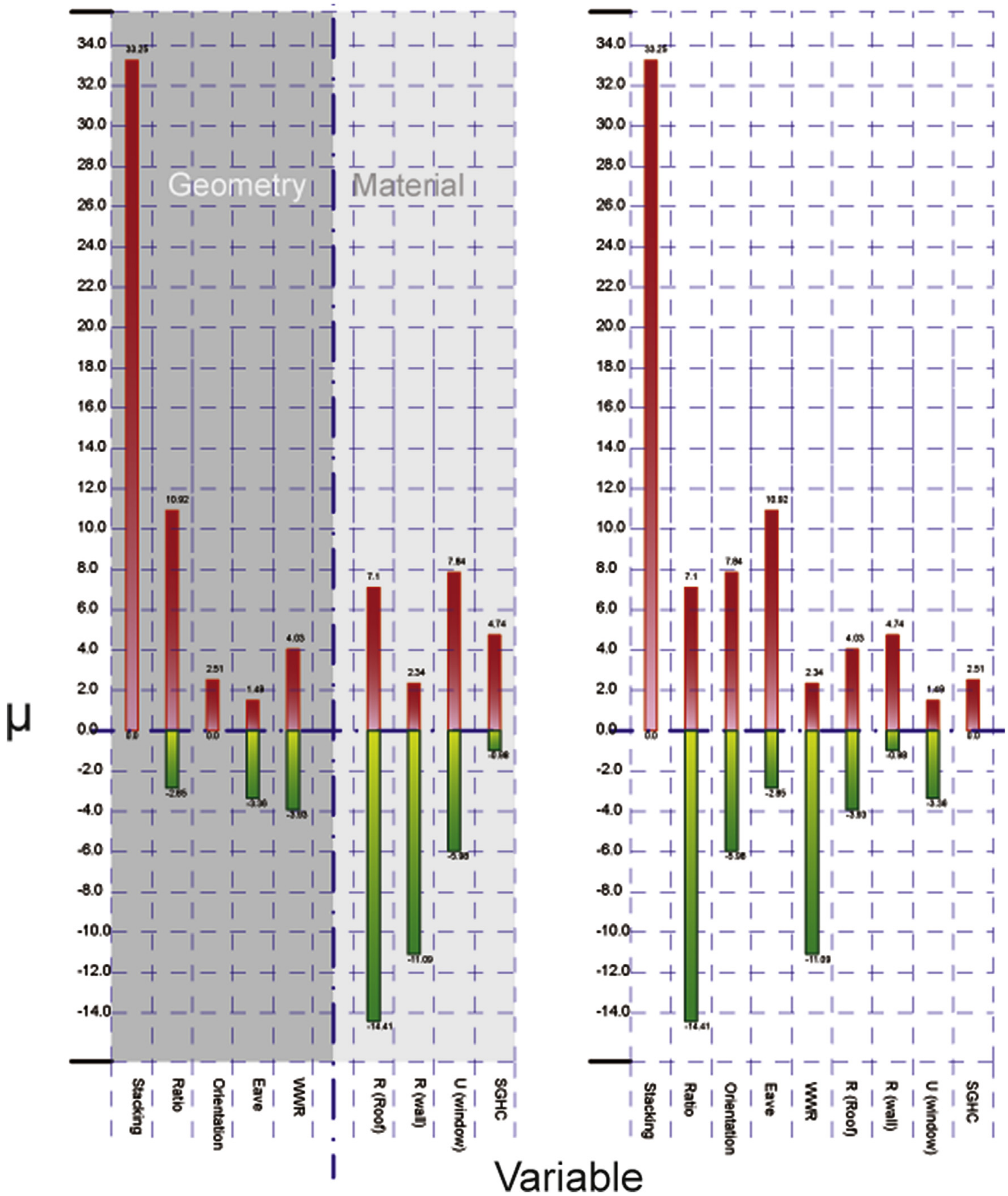

Fig. 10. Local sensitivity bar chart for **Phoenix, AZ** showing grouped vs. ordered organization.

Table 4
Local sensitivity prioritized by importance factor for each variable for Lincoln, NE.

Ranking	Variables	Importance
1	R (Roof)	15.19847
2	Stacking	14.25669
3	U (window)	13.59027
4	R (wall)	11.76345
5	Ratio	9.445349
6	SGHC	4.700355
7	WWR	4.046994
8	Orientation	0.926781
9	Eave	0.000177

Table 5
Local sensitivity prioritized by importance factor for each variable for New York, NY.

Ranking	Variables	Importance
1	Stacking	45.19363
2	R (Roof)	24.99115
3	SGHC	21.38081
4	Ratio	18.19923
5	R (wall)	14.56115
6	WWR	14.31607
7	U (window)	12.28909
8	Eave	11.52376
9	Orientation	2.41089

Table 6
Local sensitivity prioritized by importance factor for each variable for Miami, FL.

Ranking	Variables	Importance
1	Stacking	15.97153
2	R (Roof)	14.87028
3	U (window)	14.38719
4	R (wall)	11.89437
5	Ratio	9.391434
6	SGHC	5.767586
7	WWR	3.901897
8	Orientation	0.981635
9	Eave	0.470395

Table 7
Local sensitivity prioritized by importance factor for each variable for Phoenix, AZ.

Ranking	Variables	Importance
1	Stacking	33.25308
2	R (Roof)	21.50987
3	U (window)	13.81579
4	Ratio	13.7718
5	R (wall)	13.431
6	WWR	7.961874
7	SGHC	5.714387
8	Eave	4.84826
9	Orientation	2.513498

Table 9
Global sensitivity prioritized by importance factor for each variable for New York, NY.

Ranking	Variables	Importance
1	WWR	36.125026
2	SGHC	15.698453
3	U window	1.886442
4	Ratio	1.664458
5	Stacking	1.56898
6	Eave	0.464746
7	R wall	0.106067
8	Roof Insul	0.04023
9	Orientation	0.009071

Table 10
Global sensitivity prioritized by importance factor for each variable for Miami, FL.

Ranking	Variables	Importance
1	WWR	60.357531
2	U window	15.925347
3	SGHC	3.969144
4	Ratio	3.50046
5	Stacking	3.179524
6	Eave	0.577843
7	R wall	0.546566
8	Roof Insul	0.114783
9	Orientation	0.013266

performing buildings or low-energy architecture. Outlined herein is a method for including geometric aspects of buildings in a sensitivity analysis, which may aid as a viable decision-making instrument in the design process. Building geometry of stacking and aspect ratio do affect the energy performance of the residential scale of buildings evaluated in each of the four U.S. locations.

From the stacking and aspect ratio analysis, a compact form is the most efficient. geometry for residential buildings. The analysis coupling these two geometric variables The comparison made in Fig. 6 shows this where stacking level 2 crosses below level 1. This is the case when looking at the annual energy performance across all four locations. Additionally, Figs. 7–10 demonstrate that the effect of aspect ratio specifically is more significant the further north or south of the equator the building is located. Finally, since stacking is an alternative expression of compactness. The analysis completed validates the results of Gratia and Herde's [5] analysis where the most compact two-story form had the best energy performance.

There are also other issues to consider and justifies the geometric calculations necessity. The R-value of the roof is usually greater than the R-value of the walls (and definitely the windows for that matter). Therefore, the bigger surface of the roof might also improve the total R-value of the building. Thus, this might not be a geometrical property; rather it is applying more of the roof surface (better insulating material). Additionally, one side of the building touches the ground (the floor) and so there is no thermal convection there. Often the ground has higher insulation value and bigger square footage on the ground level might improve the total performance of the building.

In either sensitivity method presented, the variables decided upon for the analysis and the sensitivity approach used are both subjective and depend on the design objectives, climate conditions, building type and more. In other words, alongside the design the decision-makers should consider the building goals and objectives to inform the composition of the sensitivity as a concurrent activity. These decisions affect aspects of the geometry studied, for instance, shape factor (aspect ratio + stacking) in a sensitivity analysis does depend on the range and in turn affects the GSA outcome [25].

Climate variations, while not a specific area of interest for the study, are visible in the scale and magnitude of different between the sensitivity charts. Due to the increases in energy use from cooling or heating in different climates, therefore the importance and different prioritization varies across locations, suggesting that geometry should vary from climate to climate and understood at a local level.

There is limited research on the impact of geometry factored into the two types of sensitivity analyses. Of the sensitivity analyses reviewed [21–23,25–31], few focus on geometry and primarily factor in occupant behavior, mechanical, electrical, daylight, function, envelope variables, temperatures, and control systems. As discussed in this paper shape factor, compactness and orientation

Table 8
Global sensitivity prioritized by importance factor for each variable for Lincoln, NE.

Ranking	Variables	Importance
1	WWR	77.22728
2	U window	19.356001
3	Ratio	4.471652
4	SGHC	3.957056
5	Stacking	3.770075
6	R wall	0.698454
7	Eave	0.540569
8	Roof Insul	0.164685
9	Orientation	0.017297

Table 11
Global sensitivity prioritized by importance factor for each variable for Phoenix, AZ.

Ranking	Variables	Importance
1	WWR	55.856326
2	SGHC	18.334865
3	U window	3.785473
4	Ratio	2.847682
5	Stacking	2.566315
6	Eave	0.49039
7	R wall	0.274797
8	Roof Insul	0.074796
9	Orientation	0.014674

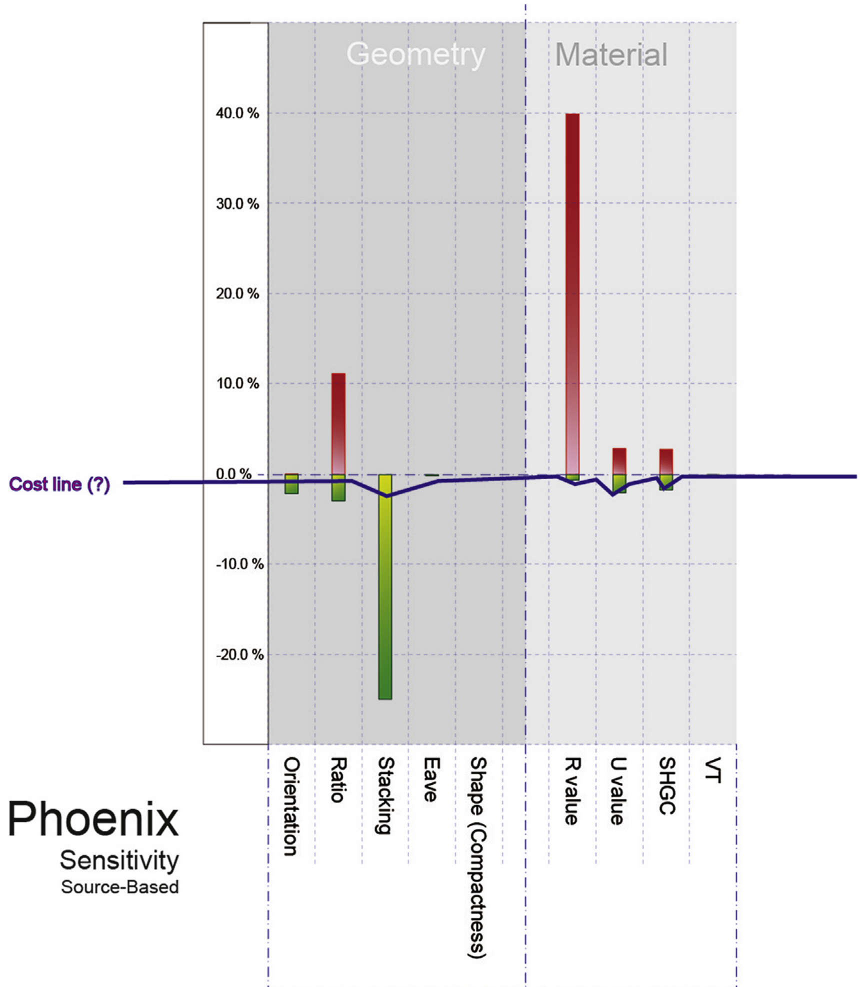

Fig. 11. Hypothetical SI chart including the least cost guideline.

are common variables requiring study using sensitivity analysis for decision-making.

However, one similar study does identify the potential of parametric modeling and energy modeling linkages to evaluate early design decisions about a building's geometric characteristics [32]. The case study chosen by Nembrini et al. [32] for this particular test of a sensitivity analysis limits the design variation to an urban context where fenestration and interior volume are the primary design considerations.

Alternatively, the publications reviewed focusing on geometry [5–12,16–18] investigate a wide range of formal potential. However, they lack a connection of the geometric research to the all the others various inter-related design elements effecting energy performance highlighted in sensitivity analyses.

Accordingly, the research proposes a pre-design sensitivity analysis using the GSA proposed by Heiselberg et al. [21] to include geometric considerations, the analysis is albeit more complicated to complete, however the a range of variables produced earlier has impact earlier in design due to understanding the inter-relationships. Variables evaluated for buildings have various different effects on energy performance; for example, increasing daylight might decrease electric lighting but increase heating loads. The design decision-making tools shown [23] and [24] are unable to outline this complexity.

Since the geometric considerations incorporated into the SI and GSA defines the range of variation as values, it may not provide enough information for adequate decision-making. Including the use of auxiliary cost-lines could reflect the cost of the geometric modifications. For example, a hypothetical example shows an arbitrary line, Fig. 11. The idea is that geometric pre-design modifications have the least amount of cost, while material modifications are more costly (upgrading the R-value for example). In addition, a second curve could help understand how much savings is achievable by this upgrade (not included in the picture).

5. Conclusion

Analyzing building geometry using aspect ratio and stacking were included in local and global sensitivity analysis. These two aspects of a building's geometric form have in some cases depending on location more impact on a buildings energy performance than the materials utilized in the building envelope. Outcomes provide building designers clarity on the formal variations in the early design phase informing design decision-making.

Considering that the surface area has an impact on the savings the above analysis is helpful in evaluating which horizontal or vertical proportions are ideal. Including the building's geometry into sensitivity analyses expands the range of design decisions beyond those typically used.

For building energy modeling software, which incorporates decision-making sensitivity analysis tools for use in design, there is a need to make explicit the methodologies used for the benefit of adequately understanding them to make design decisions. In addition, there is benefit to include a range of SI and GSA analysis, due to how an individual building element performs by itself is different from how it relates to other elements.

Finally, it is important to understand how the creation of a sensitivity analysis in order to effectively leverage this instrument as part of decision-making. Understanding the different types of inputs and their relationship to reality can provide useful information for decision-makers.

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References

[1] Olgyay V. Design with climate: bioclimatic approach to architectural regionalism. 1st ed. Princeton University Press; 1963.
[2] Allen E, Iano J. The architect's studio companion: technical guidelines for preliminary design. Wiley; 1989.
[3] Ross BM. Design with energy in mind. School of Architecture Master Thesis. University of Waterloo Library; 2009.
[4] American Society of Heating. Refrigeration, and air-conditioning engineers, (ASHRAE), 50% advanced Energy design guide for small to medium office buildings. Retrieved from:. 2012. https://www.ashrae.org/standards-research—technology/advanced-energy-design-guides.
[5] Gratia E, De Herde A. Design of low energy of office buildings. Energy Build 2003;35(5):473–91.
[6] Ourghi R, Al-Anzi A, Krarti M. A simplified analysis method to predict the impact of shape on annual energy use for office buildings. Energy Convers Manag 2007;48(1):300–5.
[7] Depecker P, Menezo C, Virgone J, Lepers S. Design of buildings shape and energetic consumption. Build Environ 2001;36(5):627–35.
[8] Straube J. Function of form: building shape and energy. Insight, Building Science.com. 2012. p. 1–4.
[9] Aksoy UT, Inalli M. Impacts of some building passive design parameters on heating demand for a cold region. Build Environ 2006;41(12):1742–54.
[10] Hachem C, Athienitis A, Fazio P. Investigation of solar potential of housing units in different neighborhood designs. Energy Build 2011;43(9):2262–73.
[11] Kämpf JH, Montavon M, Bunyesc J, Bolliger R, Robinson D. Optimisation of buildings' solar irradiation availability. Sol Energy 2010;84(4):596–603.
[12] Kanters J. Solar integrated architecture in Scandinavia an analysis of the design process. Lund University, Lund Institute of Technology; 2012.
[13] Pacheco R, Ordóñez J, Martínez G. Energy efficient design of building: a review. Renew Sustain Energy Rev 2012;16(6):3559–73.
[14] Attia S, Gratia E, De Herde A, Hensen J. Simulation-based decision support tool for early stages of zero-energy building design. Energy Build 2012;49:2–15.
[15] T. Hemsath, Conceptual energy modeling for architecture, planning and design: impact of using building performance simulation in early design stages. In. Proceedings of BS2013: 13th Conference of International building performance simulation Association, Chambéry, France, August 26–28, 2013.
[16] Wang W, Rivard H, Zmeureanu R. Floor shape optimization for green building design. Adv Eng Inform 2006;20:363–78.
[17] Tuhus-Dubrow D, Krarti M. Genetic-algorithm based approach to optimize building envelope design for residential buildings. Build Environ 2010;45:1574–81.
[18] Yi Y, Malkawi A. Optimizing building form for energy performance based on hierarchical geometry relation. Autom Constr 2009;18:825–33.
[19] Evins R. A review of computational optimisation methods applied to sustainable building design. Renew Sustain Energy Rev 2013;22:230–45.
[20] Hendron R, Engebrecht C. Building america house simulation protocols. 2010. Retrieved from: http://18.181.0.31/afs/athena/dept/cron/project/concrete-sustainability-hub/Single Family Residential/Reference Documents/2010_Building America House Simulation Protocol.pdf.
[21] Heiselberg P, Brohus H, Hesselholt A, Rasmussen H, Seinre E, Thomas S. Application of sensitivity analysis in design of sustainable buildings. Renew Energy 2009;34:2030–6.
[22] Lam JC, Hui SCM. Sensitivity analysis of energy performance of office buildings. Build Environ 1996;31:27–39.
[23] Heller J, Heater M, Frankel M. Sensitivity analysis: comparing the impact of design, operation, and tenant behavior on building energy performance. New Build Inst 2011. http://newbuildings.org/sites/default/files/SensitivityAnalysisReport.pdf; [accessed 25.07.14].
[24] Scheer D. New 'potential energy savings' widget helps you focus on what matters!. 2013. Retrieved from: http://autodesk.typepad.com/bpa/2013/05/gbs-green-building-studio-new-potential-energy-savings-widget-focus-on-what-matters.html.
[25] Capozzoli A, Mechri H, Corrado V. Impacts of architectural design choices on building energy performance application of uncertainty and sensitivity techniques. In: Building Simulation 2009; Proceedings of International IBPSA Conference; 2009.
[26] Encinas F, De Herde A. Sensitivity analysis in building performance simulation for summer comfort assessment of apartments from the real estate market. Energy Build 2013;65:55–65.
[27] Gelder L, Van JH, Roels S. Probabilistic design and analysis of building performances: methodology and application example. Energy Build 2014;79:202–11.
[28] Hopfe CJ, Hensen JLM. Uncertainty analysis in building performance simulation for design support. Energy Build 2011;43:2798–805.
[29] Azar E, Menassa CC. A comprehensive analysis of the impact of occupancy parameters in energy simulation of office buildings. Energy Build 2012;55:841–53.
[30] Tavares PFAF, Martins AMOG. Energy efficient building design using sensitivity analysis—A case study. Energy Build 2007;39(1):23–31.
[31] Smith GB, Aguilar JLC, Gentle AR, Chen D. Multi-parameter sensitivity analysis: a design methodology applied to energy efficiency in temperate climate houses. Energy Build 2012;55:668–73.
[32] Nembrini J, Samberger S, Labelle G. Parametric scripting for early design performance simulation. Energy Build 2014;68:786–98.