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EXPLORING GEOMETRIC SENSITIVITY USING RAPID ENERGY PERFORMANCE SIMULATION

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ABSTRACT

With increasing code expectations on lighting, mechanical and electrical systems more pressure is placed on the architectural design of buildings. However, little is known about the geometric sensitivity of the architectural form related to energy performance. Various studies highlight the reciprocal relationship between certain building types and specific climates. The studies are limited in that they explore single building use types, single climates, and simple building geometry. This paper will describe a custom tool titled Rapid Energy Performance Simulator (REPS) allowing design teams to explore in any climate the energy performance of extruded footprints, building orientation, window wall ratio, and aids in prioritizing shading. The REPS tool is designed to work with few initial inputs, novice software users, and early conceptual design. Analysis of resulting geometric results across climate zones provides insight into the geometric sensitivity of the building's shape on energy efficiency and validates the value of REPS for early building performance simulation of energy use.

INTRODUCTION

Research shows that geometry-based indices only correlate with a building's thermal performance according to specific climate regions and building design programs (Rodrigues et al. 2015); therefore, it is paramount to evaluate energy use with BEM during design to evaluate how modifications to a building's geometry can affect its energy use. The geometric measures below are helpful in making case-by-case comparisons between different iterations of a building design. Following this summary is the literature review discussing the research.

1. *Compactness Index (C) is a measure of the building's internal volume-to-exterior surface area (V/S), with the higher number being the most compact. It is the inverse of the Shape Coefficient below*
2. *Shape Coefficient (Cf) is the ratio of surface area-to-volume (S/V), where (S) is the sum of all surface areas in contact with the outside air and the building's enclosed internal volume (V)*
3. *Relative Compactness (RC) is the ratio of a building's compactness index (Ci) to the compactness index of a reference building, with the reference building being the more compact*
4. *Window-to-Wall Ratio (WWR)*
5. *Window-to-Floor Ratio (WFR)*
6. *Window-to-Surface Ratio (WSR)*
7. *Floor Area-to-Enclosure (F/E)*
8. *Exterior Wall-to-Floor Area (EW/F)*
9. *South Exposure Coefficient (Cs) is the southern-facing wall-to-volume ratio (Ss/V)*
10. *Shape Factor or Aspect Ratio (AR) is the ratio of the building's length to depth*
11. *Above-Grade Surface Area (S) is the surface area of the building, walls, and roof*
12. *Building Internal Volume (V) is the building volume enclosed by the ground floor, walls, and roof*

The above metrics typically quantify building geometry and come from a wide range of literature. The most common metric is building compactness. Compactness is the building's volume divided by its exterior surface area (V/S) (Gratia and De Herde 2003). While early building literature considers S to include the exterior area in contact with the ground, more recent discussions omit this from the value of S, limiting it to only the above-ground exterior surface area. This measurement is not necessarily an absolute, but you should define it for your project. If you have a large amount of belowground building area, you can either quantify this area as part of S or break the surface area into two different values for that above ground and that below, expressed as Sa and Sb.

The inverse of compactness is the shape coefficient describing the total building's surface area over the building's overall volume (S/V) (Depecker et al. 2001). When evaluating a building's geometry using these metrics, it is common to keep the volume constant: a 3,000 m3 building's energy use is very different than that of a 300,000 m3 one, though they may have the same compactness.

Another version of the shape coefficient as proposed by Jon Straube also eliminates the ground-floor area from compactness, suggesting that floor area/enclosure (F/E) is more accurate than the compactness proposed by Gratia & Herde. This not only makes logical sense, it is consistent with the research and a building's differing thermal performance with the ground versus through its walls or roof. Straube also eliminates the total interior volume from his considerations and prioritizes only the floor area, arguing that in most buildings the interior volume value is misleading due to the size of the plenum spaces that alter the interior conditioned space volume (Straube 2012). Adding to these metrics, Thomas Hootman in his book *Zero Energy Commercial Buildings* suggests that the total exterior wall area divided by the floor area (EW/F) is ideal for measuring a building's passive solar design potential (Hootman, 2012) while also using the shape coefficient (S/V), the inverse of the compactness index.

To summarize the building volume-based measures, you have compactness as the Volume/Surface Area of Building (V/S), the Floor Area/Enclosure (F/E), the Exposed Wall/Floor Area (EW/F), and the Surface Area/Volume (S/V), all of which highlight different geometric volumetric measurements of various building forms. Other two-dimensional and related metrics include the building's Quantifying Shape Factor/Aspect Ratio (the building's ratio of length to depth, L/D), along with the building's overall height (H), surface area (S), and volume (V).

Finally, research by Eugénio Rodrigues quantifies a clear and comprehensive list of variables, called d. Additionally, the window-to-floor ratio (WFR) is familiar to architects primarily because building codes require a minimal amount of windows compared to the floor area for natural lighting and ventilation. Other ratios on the geometric indices list are the window-to-surface ratio (WSR) and the Southern Exposure Coefficient (Cs), which relate exclusively to different ways of measuring the surface of the building itself. To compare the building's energy use with its geometry, it may be helpful to utilize these measurements depending on what questions you need answered.

Shown though this summary of building research studies and geometric indices allows one to correlate a building's thermal performance (its energy use) with the building's geometric metrics. Architects examining different climate zones and building shapes can benefit from understanding which specific measurement might work for the building type in the specific climate. For robust analysis results, simulations of hundreds of different building shapes are necessary, though not everyone has time to find the correlation between geometry and energy use within a particular climate. There are enough differences in each building's type, program composition, and system that no one factor can serve as a catch-all for a designer to specifically focus on; designers should instead seek balance between the most crucial factors for that building's needs.

Which piece or pieces do you emphasize to achieve the desired effect? Historically, this large solution space for building design has been a challenge. Fortunately, our computational tools today open new doors and opportunities to search this space for an approximate answer that might work. Described next is how Rapid Energy performance Simulation (REPS) addresses this challenge and allows exploration, screening, and geometric sensitivity, to aid in prioritizing results.

SIMULATION

As an initial investigation into building geometry, REPS was utilized to evaluate different shapes, use types, and locations. To begin, this section describes the functionality of REPS, followed by a screening method used to determine the geometric sensitivity, and concludes with simulation results from two separate sources. The first results come from REPS followed by results from a different tool discussed and published by the Author.

Functionality

REPS is built in the Rhinoceros 3d algorithm editor plugin Grasshopper (Davison 2018), utilizing the Ladybug and Honey-Bee (Roudasri 2018) add-ons to connect Open Studio, Radiance, Daysim and EnergyPlus. Rhinoceros is a commonly used Architectural design tool. Grasshopper introduces rule-set of controls into the 3d modeling environment automating calculations and problem-solving. In the case of REPS, the algorithm prompts users for the key architectural inputs, independent variables, to evaluate the energy performance resulting from the dependent variables of massing, orientation and WWR.

On startup, REPS uses a Human UI interface developed by NBBJ, that provides a graphic interface to input variables into grasshopper. The initial inputs determine the simulation settings that feed OpenStudio and

EnergyPlus. Aligning with the goal of ease of use and for early design analysis, little information is necessary, users assign basic values an EnergyPlus weather file (EPW) for the project location, gross square footage, floor to floor height, building's use type, and selected geometry. Leaving the other advanced settings as defaults, users can simulate the energy consumption of an array of building masses, orientations and WWR with these five inputs.

Toggling the advanced settings provides control over the range of building orientation from zero to ninety degrees, the proportion of rectangular geometry, and the WWR. In addition to the range are step values within the orientation and WWR controls. Such as ten degrees or ten percent changes within the range.

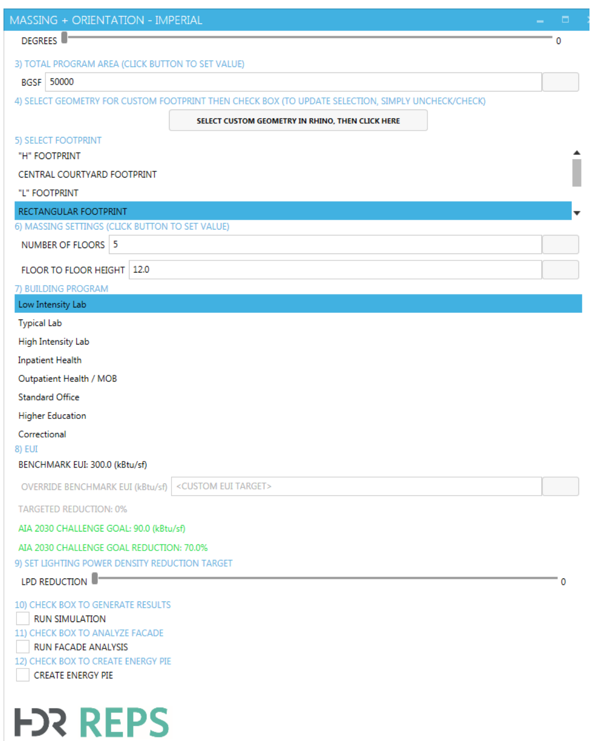

Figure 1 Example of user interface

In addition to the basic and advanced settings, the REPS tool allows user to create custom shapes adding to the default geometry provided. The default shapes include a rectangle, curved bar (C shape), courtyard, L and H shapes. Being an early conceptual analysis, the geometry analyzed is an extrusion of the footprint shape selected. To evaluate more complex building masses would require breaking the building into pieces simulating each separately then aggregating the results.

REPS simulates the combination of these variables producing an array of results in OpenStudio and EnergyPlus. Depending on the complexity of inputs results may take some time. However, with knowledge of the tools capacity processing results in a few minutes is possible. The result array spreads the different masses based upon the selected shape across a grid with the orientation differences along x axis and WWR differences along the y axis.

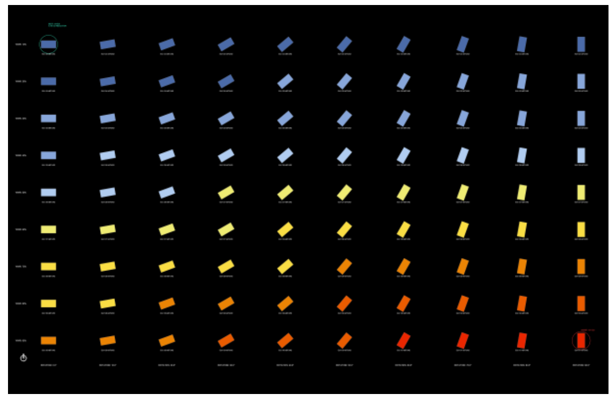
Figure 2 Example of REPS results

Outcomes of the simulation include the predicted energy use intensity (pEUI) from the key loads, heating, cooling, lighting, and equipment. To aid in understanding the output, the pEUI results are colored in a gradient from low to high pEUI and the best and worst cases are circled. One can toggle between simple pEUI and detailed energy consumption variables and from the best option produce a bar chart detailing the loads.

From this basic beginning, users can analyze the best options shading requirements. Selecting another checkbox triggers a dynamic balance point analysis to identify which elevation exposure requires shading.

Summarizing functionality of REPS, input the independent variables produces an array of different energy consumption results based on orientation and WWR. The goals of providing quick feedback and ease of use forced limits to the range of variables. Using ASHRAE 90.1 defaults for systems types, power densities, lighting controls, and equipment loads along with industry experience of the occupancy and use type settings limit the inputs to those most architecturally relevant during a project's conceptualization.

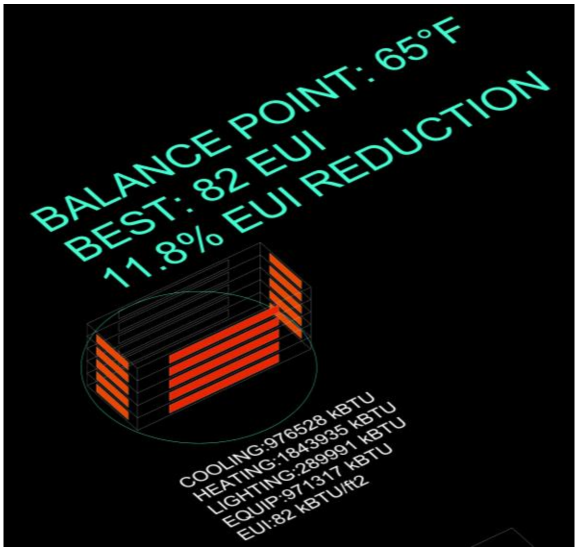

Figure 3 Example of shading results where color indicates need.

Geometric Sensitivity

Authors Parasonis and Hemsath highlight correlations between some building types geometry and climate. Using REPS, a large solution space is possible, simulating the same basic building geometry across climate zones, use types, orientations and WWR. In addition to this tool and these authors work, Hemsath and Bandhosseni (2017) published a pattern guide of various office building shapes, sizes in four north American locations. This section of the paper analyzes the geometric sensitivity of shapes from REPS and the published work mentioned previously.

Use of sensitivity analysis to compare building geometry has been utilized previously by the author (Hemsath, 2015) to evaluate smaller residential buildings. The SI represents in numerical form a similar range, equation 1.

(1) SI = (Emax-Emin/Emax)*100

From each mass the maximum (Emax) and minimum (Emin) annual energy consumption values for a climate zone summarize the overall range of performance. Expressed as a single number the sensitivity index (SI) highlights the variability of a building's energy performance and allows comparison of building orientation and mass sensitivity across and within use types and climates. The index is a numerical representation of the variability of results with the larger number being more sensitive.

Valuable to our analysis is the understanding of what the most sensitive elements are. Experience shows that for certain climates and building use types different geometric attributes are more impactful than others on energy consumption. Using the SI allows screening of the most important for further investigation and attention in early architectural design.

REPS results

For the purposes of this paper using REPS produced results for three shapes (rectangle, L, C), 90 degree orientation and 80 percent WWR change. Simulation of orientation and WWR each had steps of ten difference. The office and inpatient healtcare building square footage was fixed at 50,000 on three floors and located in Omaha, NE. An example of one simulation result is shown in Figure 2. The results were aggregated into a excel files and then screened with the SI equation 1 with the results shown in table 1. The simulation results for each variable of WWR, Orientation and an overall is represented with an SI value.

Table 1 REPS results for shapes and inpatient health and office buildings in Omaha, NE.

		RECTANGLE	L	C
OFFICE	WWR	16.5		
	Orientation	2.2		
	Overall	16.1		
Inpatient	WWR	8.8	9.5	10.3
	Orientation	1.4	1.2	1.8
	Overall	9.3	9.9	11

Office Shape results

Table 2 shows office building sizes of Small (5,000 sq. ft.), Medium (50,000 sq. ft.), and Large (500,000 sq. ft.) SI for four U.S. locaitons. The SI is derived from equation 1 using the simulated EUI results of thriteen different shaped office buildings.

Table 2 Example of Office building geometric sensitivity by location

	MIAMI	NY	OMAHA	PHOENIX
Small	15	7	9	6
Medium	39	51	50	44
Large	41	25	29	23

DISCUSSION

The results from these two tools demonstrate a how geometric aspects of a building contain potential for further energy savings. Using the screening method identifies in the tables above those areas requiring more diligent study in latter phases of design. Specific results from each clearly show that in some cases geometry is more important than others.

For example, REPS results in Table 1 separate out the impacts of WWR and Orientation from the overall sensitivity. Depending on the project and location the specific impact of these will vary. However, it comes as no real surprise that WWR is more sensitive than building orientation for this use type.

In the second case, those having a higher SI such as medium sized offices in New York and Omaha make clear that the overall building geometry matters in these climates more than others. Therefore, further analysis of whether energy performance for medium size offices has a stronger relationship to the building's geometry is necessary.

CONCLUSION

This paper highlighted the value of understanding the energy impact of building geometry. Simulating various building sizes, shapes, uses, orientations, WWR, and locations screened with the sensitivity analysis describes the energy use impacts of these building elements. Given the data rich modeling environments at our displosal further identification of a building geometry's impact on energy use.

The two examples come from customized digital design tools leveraging algorithmic approaches to energy modeling in early design. Usability is important to provide understandable feedback to architects without much fuss or overly technical inputs. While beneficial to early design, the purposeful editing of inputs would be undersireable in latter detailed design phases.

Lacking in this area of research is a clear correlation between the overall geometrical aspects of buildings described by the indicies. The tools of today such as those utilized evaluate many aspects but omit articulating aspects of geometry.

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