

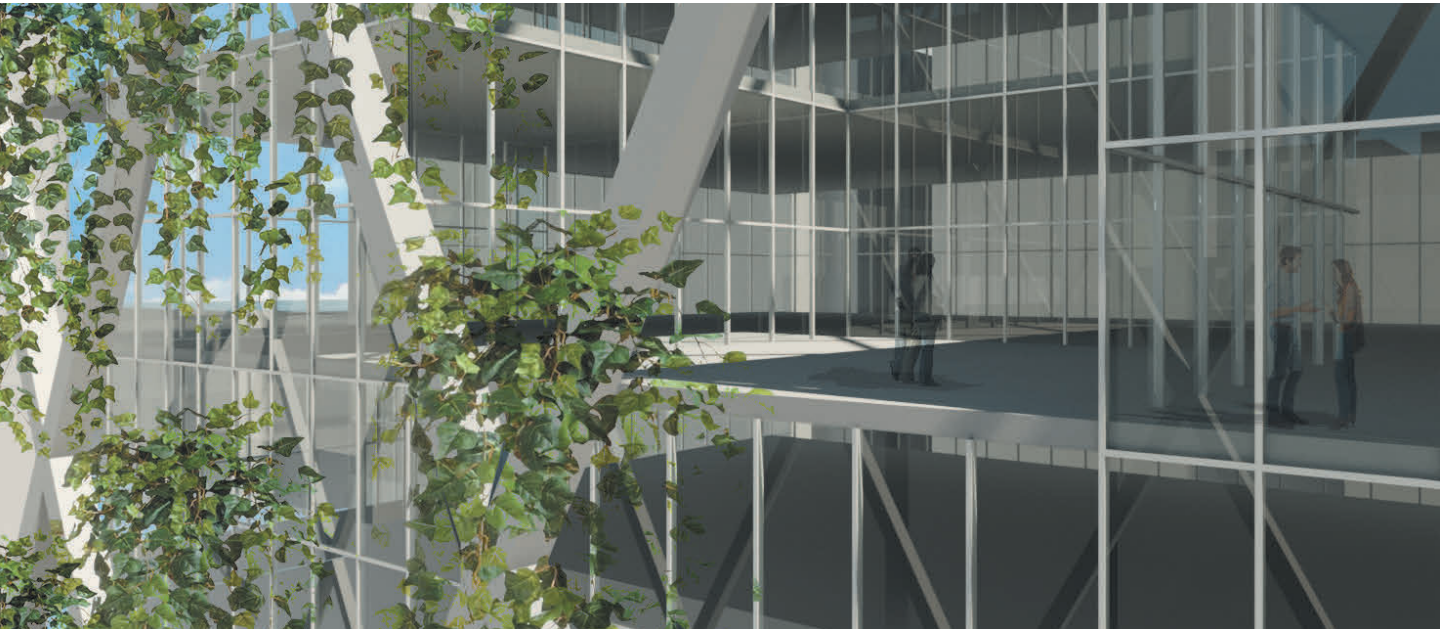
Buildable Performance Envelopes

Optimizing Sustainable Design in a Pre-Design Phase

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ABSTRACT

The growing consciousness regarding ecologically conscious architecture mandates a deeper understanding of the strategies that may be adopted by designers towards achieving this goal. With the advent of building information modelling (BIM) and the associated paradigm shift in the design process, it has become increasingly possible to make informed decisions earlier on in the design process. Despite this advancement, the architectural realm continues to lack computational resources that are capable of providing formal guidelines, through a generative process, that serve as a starting point for sustainable design. Towards overcoming this limitation, this paper will describe a computational tool that generates buildable *performance envelopes* in response to aspects of a site that are influential in designing sustainably: climate and context. These envelopes are created in a generative manner through the utilization of a *voxel* (three-dimensional pixel) matrix, which continually updates itself based on formal elements created by the user. Facilitating the process of making ecologically conscious design decisions at the earliest stages of design, which is the primary goal of this tool, more substantially increases the achieved energy optimization.

Illustrative building designs presented in the paper resulting from the testing of this tool in contrasting climate zones, such as Miami, Florida (ASHRAE Zone 01) and Aspen, Colorado (ASHRAE Zone 07), confirms the assertion that the performance envelopes generated with this tool serve only as a guideline for optimized sustainable design, and not as the final form of the building itself.

- 1 View of the office building and its façade designed based on the buildable performance envelope generated by the tool, in Miami, FL.

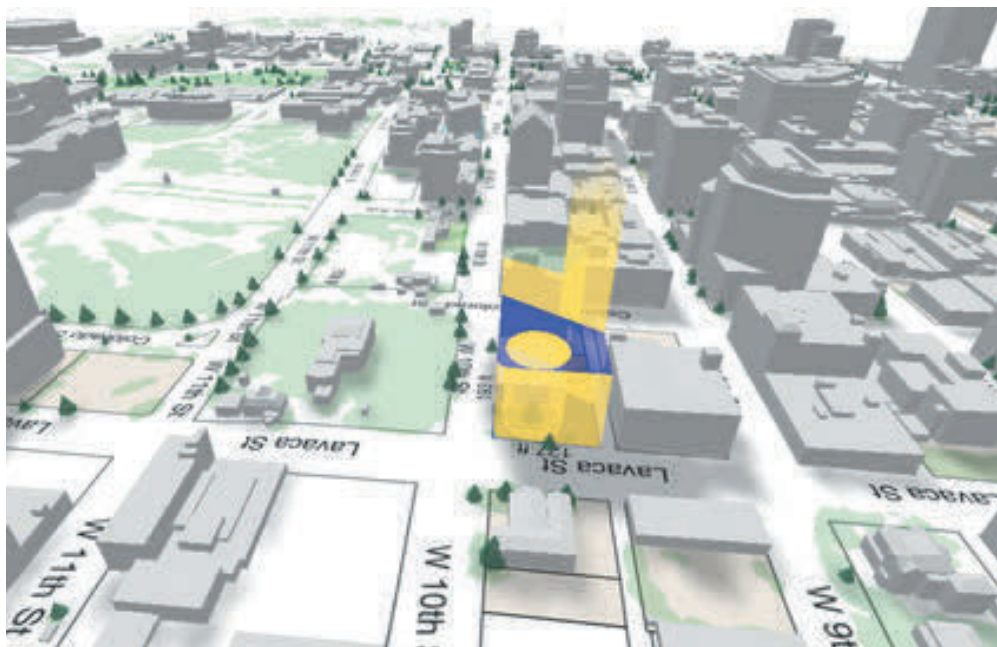
INTRODUCTION

Owing to the tremendous impact that the discipline of architecture has had on the planet in terms of energy consumption, designers need to be enabled to evaluate the impacts of their design decisions from the very initial stages of schematic development. According to architecture critic Reyner Banham (1969), two types of solutions exist for most obstacles encountered in the architectural discipline's approach to building conditioning, namely the structural solution and the power operation solution. Most buildings from the late twentieth century and the early twenty-first century rely on the latter as their sustainable solution; incorporating power consuming active systems to develop comfortable interior environments. If the former approach of implementing a structural solution or a passive design strategy during the initial design stages is adopted, a more holistic approach to a building's conditioning can be achieved, wherein energy is not further added to the system. The earlier that a designer incorporates sustainable strategies, the more substantially energy consumption is reduced and energy optimization is increased (Goldman n.d.). Furthermore, the energy optimization achieved leads to an increased efficiency of the active systems as well, implying that as a potentially low-energy solution, passive design should be the necessary first step towards ecologically conscious architecture.

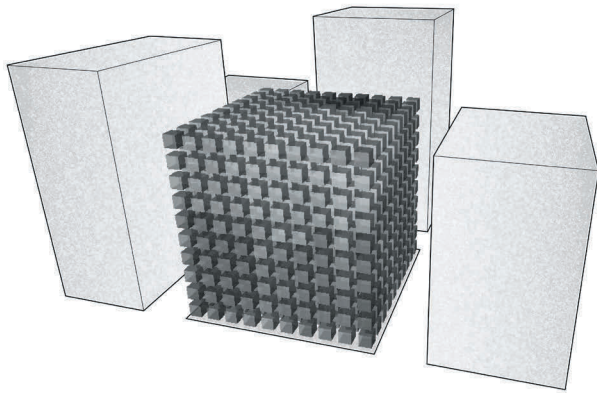
The advancements in the field of building information modelling (BIM) have facilitated informed decision making in increasingly early phases of design development. However, an inconsistency that exists in this regard is the lack of a computational tool that

provides the foundation from which passive design decisions can be conceived. To overcome this limitation, and to ensure the facilitation and dissemination of this sustainable ideology to designers everywhere, the creation of a computational tool integrated into widely utilized software within the discipline, such as Autodesk Revit and Dynamo, is imperative. Building form and orientation being paramount to passive design, this tool shall visualize the buildable envelope mapped to ideal energy performance in a similar fashion to the approach used by Flux (a generative tool developed by Google), wherein the maximum buildable envelope—as governed by the zoning guidelines, applicable ordinances and building codes relative to the selected site—was visualized in a three-dimensional form (Figure 2) (Deutsch 2014).

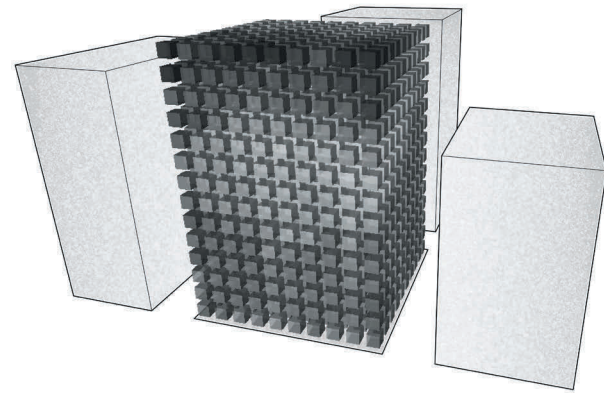
Writing, "In sustainable design, there is no one-size-fits-all," Williams (2007) alludes to the importance of site specificity in design, in that architecture responds to variations in climatic conditions. According to the Koppen Climate Classification System, the world is divided into 29 climatic categories that can be distinguished from one another due to differences in temperature, precipitation and seasonality. While this categorization provides the climatic conditions associated with a particular latitude and longitude, the concept of microclimate begins to play a pivotal role in architecture in urban centers. The increased density of buildings in such centers causes them to have an impact on the buildings surrounding them, thereby altering specific climatic variables such as incident sunlight and wind directions within a site. With a projected increase of 12% in the



2 Illustrative example of the maximum buildable envelope as generated by Flux.



3a



3b

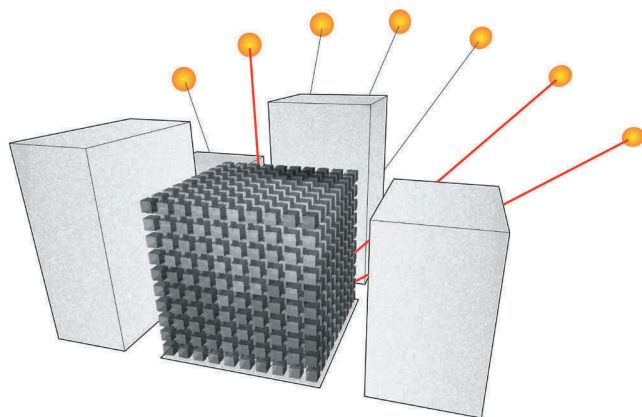
total number of people living in urban centers from the current 54%, the analysis of context begins to play an increasingly important role in determining the architecture (United Nations 2014). This paper will describe a tool that takes into account both climate as well as context to generate the performance envelope optimal for a given site.

METHODS

To begin using the tool, the user inputs data pertinent to the site, such as location (city), site boundaries and a three-dimensional model of the surrounding context, as well as data relating to the architectural elements of the project, such as floor-to-floor height, conductance values for the windows and walls, and window-to-wall ratio. The site boundary serves as the enclosing curve within which a voxel (three-dimensional pixel) matrix is generated to a height either stipulated by the user in the form of the number of floors, or defaulted to the height of the tallest neighboring building, as voxels above this height will no longer be influenced by context (Figure 3). Based on the name of the

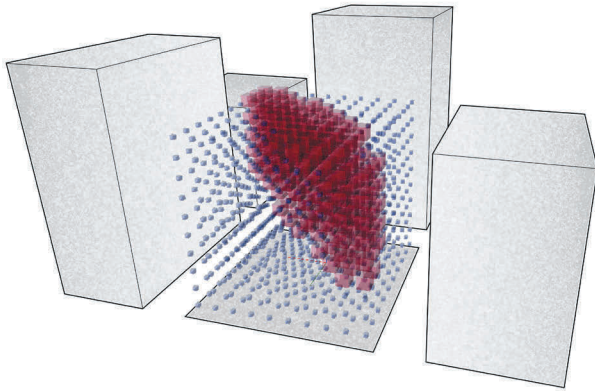
city input by the user, the appropriate weather file is selected to create the sun path specific to the site. The context plays a pivotal role at this juncture, as the sun rays that are directly incident on the site are culled for the analysis period specified by the user (Figure 4).

The values for the intensities of direct radiation are extracted from UCLA's Climate Consultant in order to assign each voxel in the matrix with a number representing the final cumulative intensity of the radiation incident on it over the analysis period. This cumulative value is computed by analyzing the voxels that are activated during each hour over the analysis period, and adding the value of intensity associated with that hour to the activated voxels (Figure 5). Furthermore, the voxels are also colored based on their associated cumulative intensities, with the colors ranging from blue to red, where the former represents the coolest or the lowest cumulative intensity, and the latter represents the warmest or the highest cumulative intensity (Figure 6).

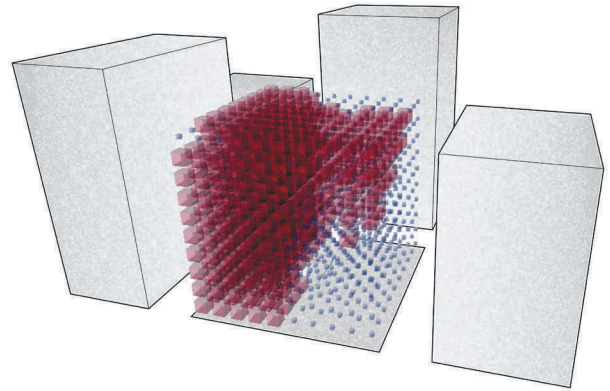


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Once this voxel matrix is generated, it is optimized for the climatic variable(s) that influences form. For the testing of this tool, the thermal aspects of solar radiation were used, which include energy gains and losses across the envelope through conduction and radiation. As the base load in any typical building (lighting loads, mechanical loads, etc.) is not dependent on the variation in the outdoor air temperature, it is only the heating and cooling loads that are being analyzed to understand the addition/reduction to the overall energy consumption (Figure 7). However, an input for the total base load for the building provides the user with the opportunity to include this value in the calculation, in order to determine whether the building will be heating- or cooling-load dominated. Since the window-to-wall ratio, which affects the total heat gained or lost through the windows and walls, is one of the primary variables for an envelope, its value is set by the user.



5a



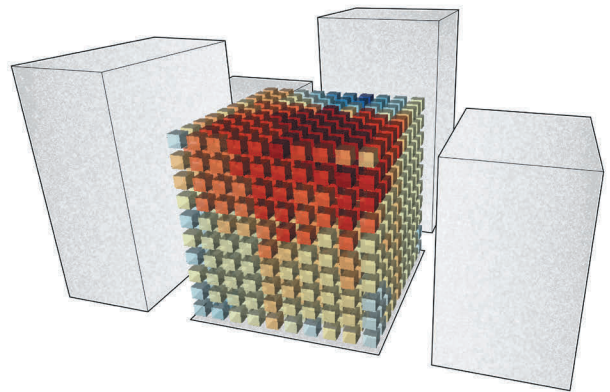
5b

The total heat gained or lost through the envelope is visualized in terms of its economic impact to better understand the direct implication of a design decision with regard to the energy cost it would engender. It is important to note that in a hot city such as Miami (ASHRAE Zone 01), an increase in the window-to-wall ratio causes a considerable increase in the cooling cost in comparison to the decrease in heating cost owing to passive solar heat gain, thereby causing an overall increase in the thermal costs. In contrast, in a cold city such as Aspen, (ASHRAE Zone 07), the increase in the window-to-wall ratio, and the associated increase in passive solar heat gain results in an overall reduction in the thermal costs.

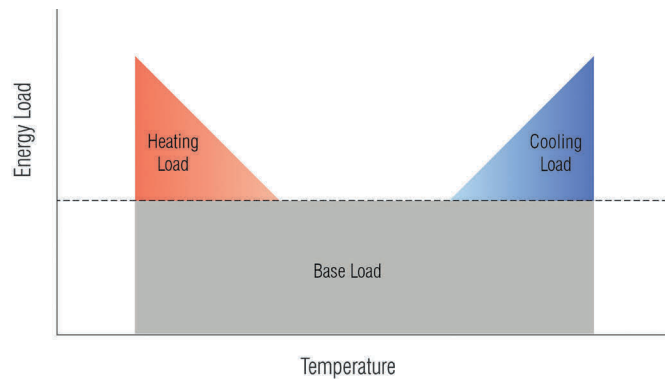
The envelope is visualized using a matrix of voxels, in which the size of each is determined by the user. The voxels in the generated matrix are then scaled and colored based on the results of the evaluation, where the larger voxels are either the ones with greater values of incident radiation in a heating-load dominated site (as determined by the evaluation process), or the lower values of incident radiation in a cooling-load dominated site (Figure 8).

In order to better understand and visualize the resultant voxel matrix, a number of features are made available to the user to improve their ability to include and interpret the evaluation results. These features include:

- The ability to select the percentage of allowable intensities to cause the disintegration of the matrix in order to display only those that fall within the allowable value (Figure 9)
- The ability to view the sectional quality of the matrix along any of the three axes, to better understand the nature of the matrix at every level (Figure 10)

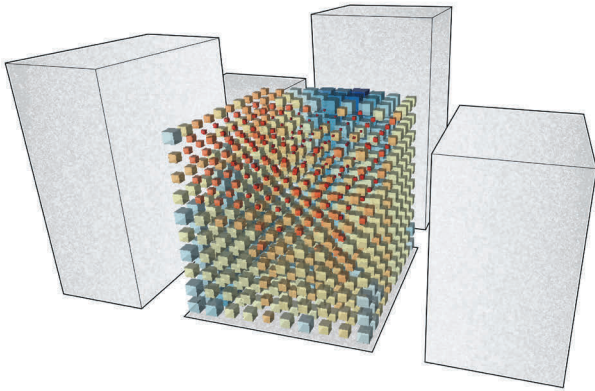


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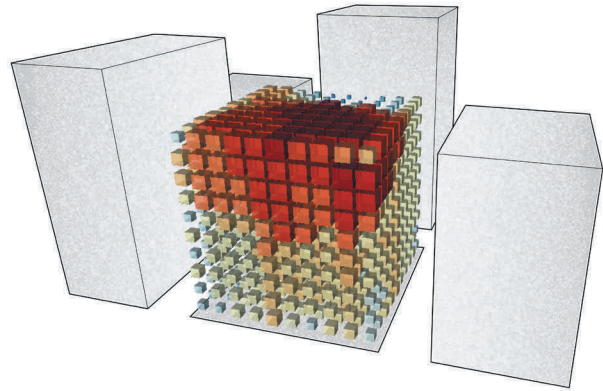


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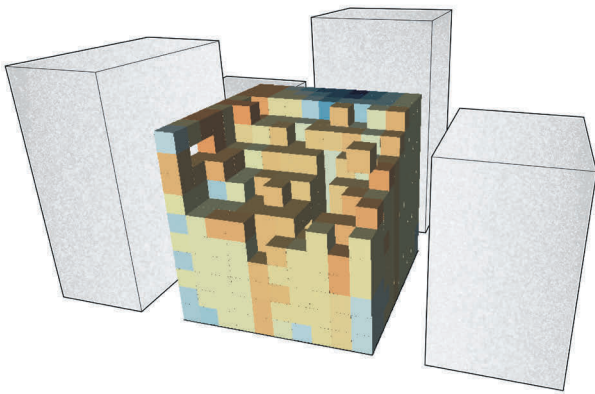
- 3 Voxel matrices generated on the selected site with a) the height input by the user and b) default height.
- 4 The sun rays directly incident on the voxel matrix being culled.
- 5 Activated voxels during an hourly analysis on 21st December 2017 at a) 09:00 am, and b) 01:00 pm.
- 6 Voxels in the matrix colored based on the value of intensity of incident radiation associated with them.
- 7 Graph illustrating the relationship between the outdoor temperature and energy loads within a building.



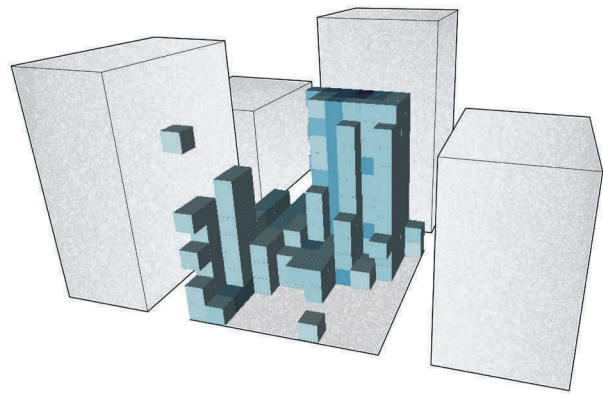
8a



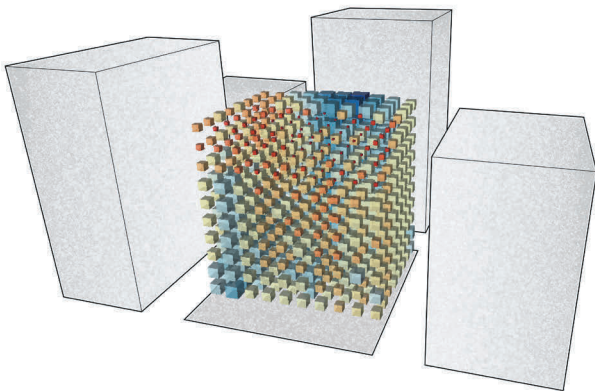
8b



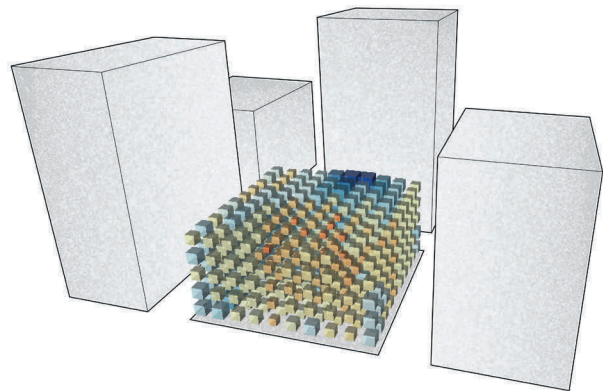
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9b

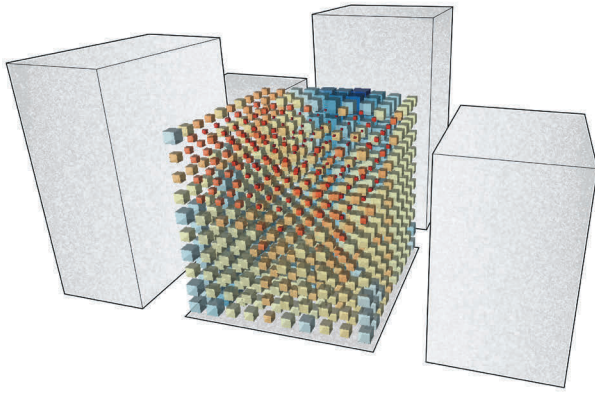


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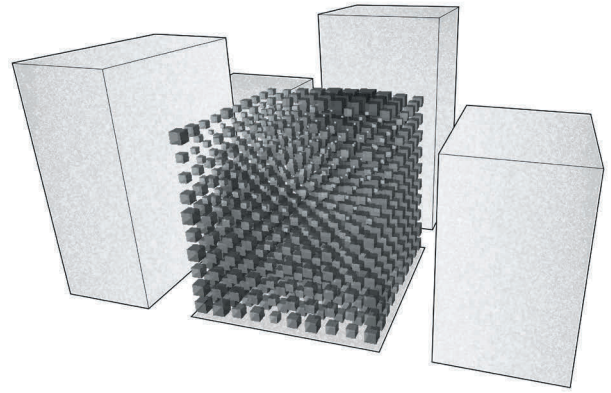


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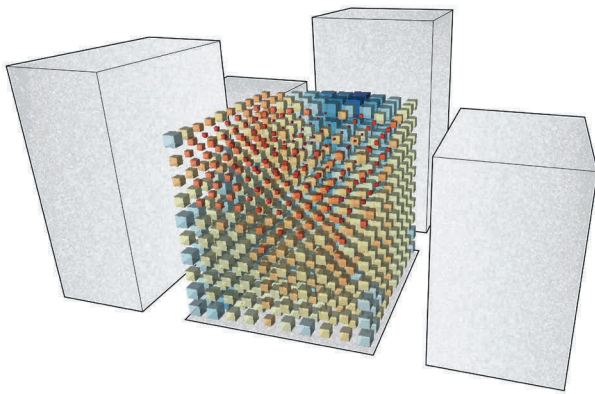
- 8 Scaled voxels in the matrix in a) a cooling-load dominated site, and b) a heating-load dominated site.
- 9 Voxel matrix with the percentage of allowable intensities set to a) 70% and b) 40%.
- 10 Sectional view slider of the voxel matrix set to a) 80% along the y axis, and b) 40% along the z axis.



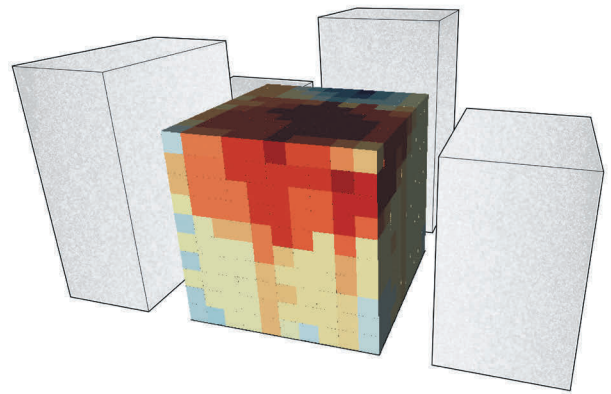
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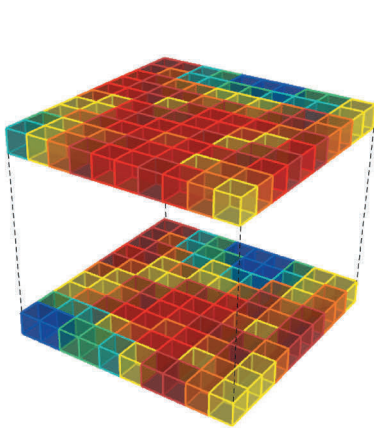
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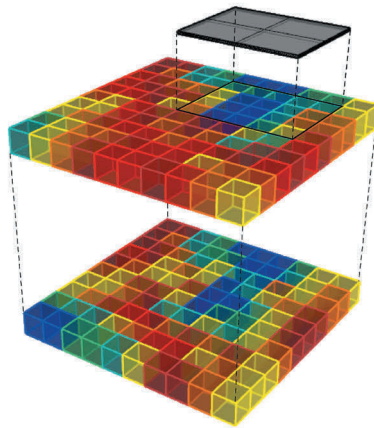
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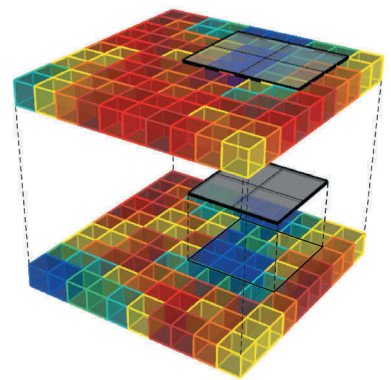
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13a



13b

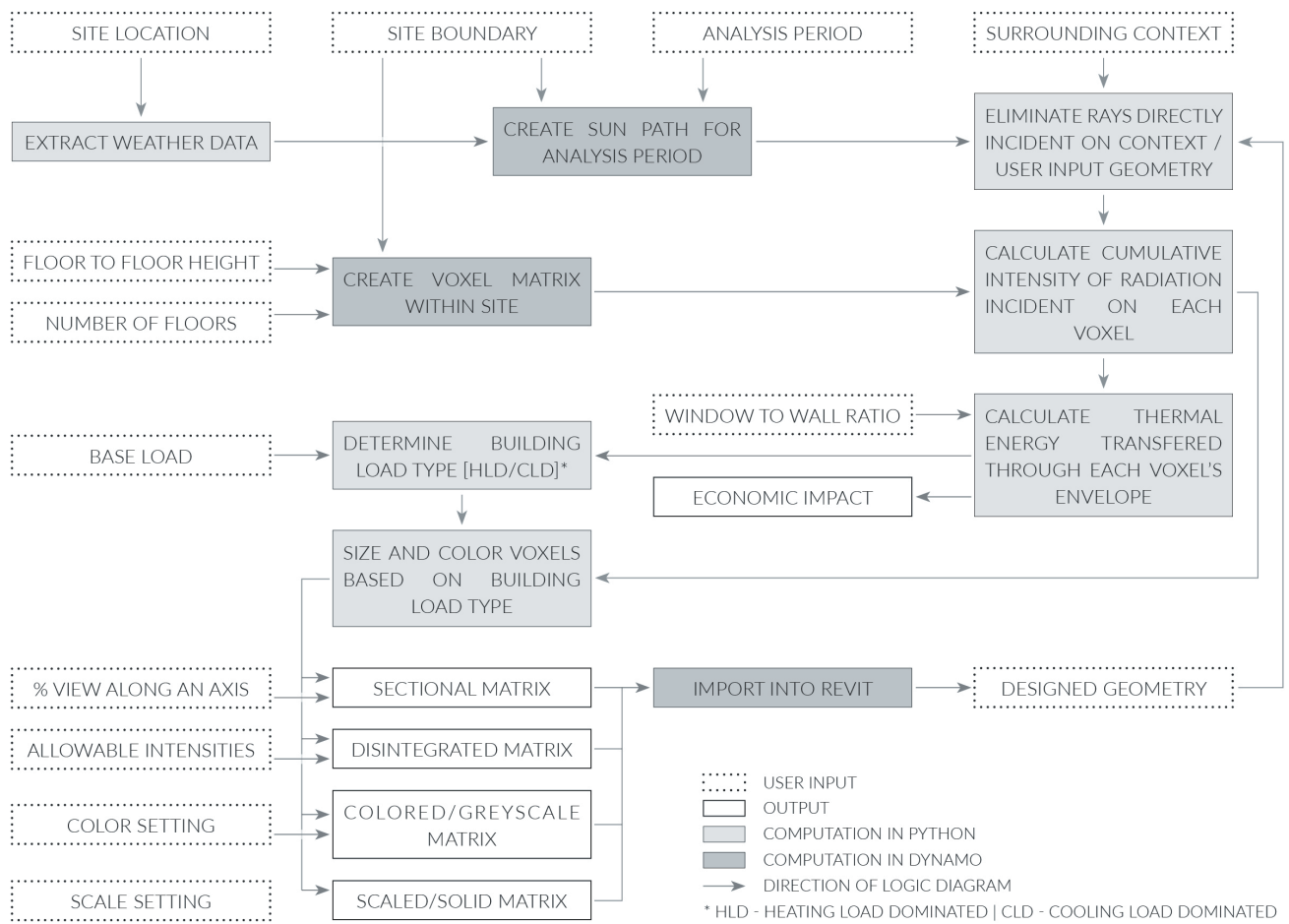


13c

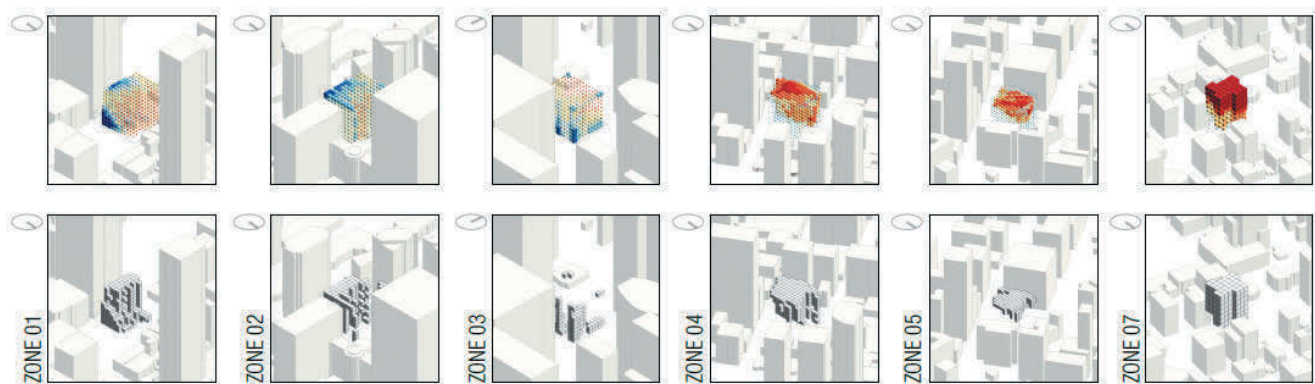
11 Voxel matrix viewed with a) scaled, colored voxels and b) grayscale voxels.

12 Voxel matrix viewed with a) scaled, colored voxels and b) unscaled, volumetric voxels.

13 a) Base voxel matrix, b) updated voxel matrix in response to addition of geometry, and c) updated voxel matrix in response to addition of another geometry below it.



14 Logic diagram illustrating the step-by-step working of the tool.



15 The base voxel matrices and voxel matrices with allowable intensities set to 50% for all six example sites.



16a



16b

16 Schematic design solutions developed based on the voxel matrices generated for the sites at a) Aspen, CO, and b) Miami, FL.

- The ability to view the voxels, either in grayscale or with the colors generated to represent the intensity of direct radiation incidence (Figure 11)
- The ability to view the matrix with the voxels either appropriately sized by the evaluation process, or as a volume (Figure 12)

This voxel matrix serves as a starting point for the design, where the user is free to use the matrix as a base in Revit to begin developing floor plates or conceptual masses. The creation of any geometry results in an updated voxel matrix due to the direct solar radiation impact that it would have on the voxels beneath it, in a similar manner to the impact that the context has on the site. Each additional floor plate is evaluated recursively in the tool, visualizing the respective impact of each. Since the solar radiation impact of any geometry is only on the voxels beneath it, a literal top-down approach from the top of the building is adopted (Figure 13).

RESULTS

To test the hypothesis, we chose six cities falling under six different climate zones (as defined by ASHRAE) in the United States: Miami, Florida (Zone O1), Phoenix, Arizona (Zone O2), Atlanta, Georgia (Zone O3), Seattle, Washington (Zone O4),

Detroit, Michigan (Zone O5) and Aspen, Colorado (Zone O7). Figure 15 illustrates the voxel matrices generated for each of these six urban sites, as well as the matrix generated with the amount of allowable intensities set to fifty percent. From these six cities, Miami and Aspen, due to their extremely contrasting climatic conditions, were chosen to begin an evaluative schematic design in order to better understand how the process in which the generated matrix aids the design process (Figure 16). In both instances, additional factors were considered for the design, including urban context, vehicular and pedestrian circulation around the site and views from the site. In Miami, of the three factors, views provided the most resistance to the form generation based on the voxel matrix; regardless of the information displayed by the voxels, views played a critical role in determining square footage on each level. In mediating between the two, additional passive strategies (such as deep overhangs, thermal mass etc.) were considered to generate a feasible form for a speculative office space while maintaining the energy consumption data being represented by the voxels. Balconies created deep overhangs on the eastern façade to ensure that direct sunlight would not be incident on the glazed surfaces while still providing views of the ocean, thereby maintaining the energy costs within the same range (Figure 17).

CONCLUSION

The voxel visualization approach to analyzing a site for various climatic variables, with the aim of generating an envelope that is responsive to them, creates a new integrated method for visualizing sustainable methods early on in the design process. The tool described in this paper adopted the thermal aspects of solar radiation as the climatic variable to respond to, but the overall approach and script is not restricted to this variable only. Climatic data pertaining to wind directions and velocities, as well as the lighting component of solar radiation (daylighting), are variables that can be plugged in to generate an envelope that is energy efficient in many regards. The end goal of such a tool would be to be able to analyze a site for a myriad of climatic variables, either in a cumulative manner or as separate layers that can be weighted depending on the most influential factors for a specific location.

Current computational limitations restrict the user from going below a certain voxel size and beyond a certain number of voxels. However, with the rapid advancements in computational and graphics processing, smaller voxels can begin to be adopted for this tool, allowing for a shift from the rigid, rectilinear envelopes that result from the current analysis, to more free-flowing organic envelopes. With the form of the envelope no longer a limitation, the designer can adapt their own aesthetic and formal style to the design in order to develop complex building shapes from this envelope, while maintaining the ideals of ecologically conscious architecture.

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IMAGE CREDITS

Figure 2: Google[x] Startup Flux, 2014

All other drawings and images by the authors.

Elizabeth Thariyan graduated from the University of North Carolina at Charlotte with a Master of Architecture degree. The work presented in this paper is part of her graduate thesis, which focussed on advancing Sustainable Architecture through the lens of Computational Design.

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17 Eastern façade of the office building in Miami, FL, designed with deep overhangs to allow views out without compromising on its energy consumption.