Eabbit 1.0: New Environmental Analysis Software for Solar Energy Representation

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Abstract

Given the challenges to designing high-performance buildings, the use of Building Performance Simulation (BPS) tools during the early design phase is indispensable. There are many tools for evaluating solar impact on buildings, ranging from energy use to daylighting and renewable energy. However, no tool accurately reflects architects' needs; all lack clear communication and proper visualization methods. This research addressed energy consumption and production measures impacted by exposure to the sun. The goal was to create a new type of early design decision support tool that functioned without running BPS optimization and parametric simulations. This was accomplished by developing important solar algorithms that were then used in a new method of solar representation for building design. It is important that usability assessments of this type of tool be conducted, especially with regards to its ability to satisfy architects' needs during the design process. However, such research is not yet common in the field of BPS. Thus, in the present research, user experiments were conducted to evaluate the effectiveness of *Eabbit 1.0*'s key interface. The results of these experiments illustrate the impact of the proposed method on annual heating and cooling consumption. The results show that tool will assist users in making significantly better decisions regarding the installation of photovoltaic panels and other issues related to solar energy.

Introduction

As building simulations and multifaceted workflows are becoming more frequently integrated into architectural design, the need for interactive building plans and simulations continues to grow. However, while prevalent, building information modelling (BIM) and building performance simulation (BPS) tools are limited with regards to generating complicated building shapes and optimizing the analysis process. Moreover, most tools assess building energy use once a schematic design is confirmed. This typically requires a significant modelling effort, especially whenever architects change the geometry of their buildings. This unbalanced workflow limits the ability of sustainability consulting to make design changes and restricts design options (see Figure 1). Parametric modelling, however, can make this process more efficient during the early design phase. Existing BPS tools require detailed input parameters to produce accurate estimates of various aspects of building performance; thus, they are more frequently used in later design stages.

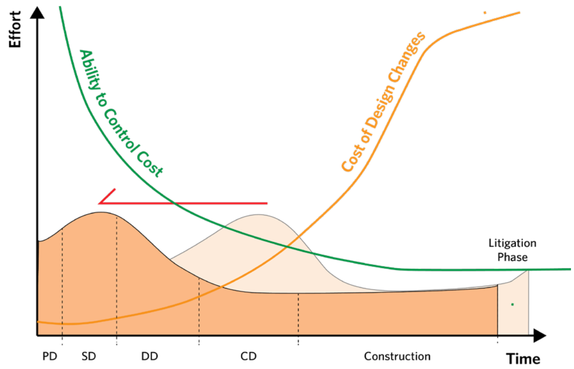


Figure 1 Design cost effort by design phase.

Parametric design strategies are increasingly being recognized in the design industry as a means of creating and visualizing sophisticated figures. The serendipity of this process is that parametric modelling application tools like Rhinoceros and Grasshopper offer architects instant visual feedback regarding their manipulations of form and space (Roudsari et al., 2013). Allowing architects to gauge the environmental validity of their creations during the design phase will increase profit and facilitate a deeper contemplation of environmental issues. Universal ways of employing BPS tools in the modelling interface will encourage more architects to actively participate in environmental analysis.

Motivation

BPS has matured into a field that offers unique expertise, methods, and tools for building performance evaluation, drawing its underlying theories from different disciplines (Augenbroe et al., 2004). Traditionally, most of the foundational work on BPS was developed and validated in the mechanical engineering disciplines, addressing the needs of engineers and resulting in increased efficacy, speed, and accuracy. While the energy, fundamental equations, and implementation were all accomplished in the early 1970's, design process integration and the creation of user-friendly tools have yet to be achieved; communication and visualization of the results tends to be poor (Weytjens et al., 2011). Therefore, the majority of BPS software offers limited accessibility to designers, especially in terms of the integration of an intelligent design knowledge base, user-friendliness of the interface with regards to usability and information management, and interoperability of the building modeling exchange (Attia et al., 2012). The knowledge-based assistance needed for design decisionmaking and user-friendly interfaces accounts for about 60% of architects' needs (Attia et al., 2012). An intuitive user interface design for BPS and the integration of key BPS knowledge is required (Farzaneh et al., 2015). Furthermore, usability testing of the software in the early development process is essential to a user-centered design approach (Cozza et al., 2018). This research developed a new tool for solar analysis by taking basic solar engineering as the main engine. Then the methods established for visual representation were investigated and assessed through a human-subject research process.

Methodology

The sun is the primary factor determining the thermal environment of built areas (Oh & Haberl, 1997). Therefore, understanding the location of the sun and estimating the intensity of the solar radiation received are important guidelines for architects seeking to understand, control, and utilize thermal effects in their building designs. Two-dimensional (2D) sunpath diagrams have been used widely by architects to evaluate the sun (Dubois, 2000). Due to the easy-to-read characteristics and adaptability of 2D sunpath diagrams, complicated analysis and calculation methods can be integrated into conventional representations. By overcoming the shortcomings of conventional sunpath BPS tools, receptive and intuitive analysis functions can be offered and integrated into the three-dimensional (3D) modeling environment. In the present work, a local weather model was developed to manipulate a current EnergyPlus weather (EPW file with a fitted time-series statistical model, using the measured data available from the National Solar Radiation Database (NSRDB) and predicted diffuse radiation values. The following section suggests effective 2D and 3D sunpath forms available from a feature integrated into the modeling interface.

2D representation of a sunpath

Solar shading devices can reduce a substantial amount of cooling load, and the different levels of window transmittance available can increase radiation penetration during the winter, diminishing the heating load. This can reduce the energy burden between 23% and 89%, depending on the type of shading device, building orientation, and local climate where such passive design strategies are applied (Dubois, 1997). Therefore, solar analysis of building facades can be beneficial for designers seeking to engage intuitively with passive building design. To inform such architects, sunpath diagrams are now widely used in design practice.

Even though there are numerous design tools for producing sunpath diagrams and design evaluations, polar sunpath diagrams (Olgyay, 1957) and orthographical sunpath diagrams (Mazria, 1979) are the most popular. The Olgyay diagram uses a polar projection of the sun onto a horizontal plane, while the Mazria method employs a cylinderical projection of the sun onto a vertical form. Both yield 2D diagrams, where the abscissa and ordinate values offer information regarding solar azimuths and altitudes, and each curve connects coordinates of the sun to show the solar time radiating away from the south (Dubois, 2000). Mazria's projection method offers certain advantages to the study of a façade's elements, such as shading devices and vertical and horizontal louveres. However, the tradiational methods of integrating Mazria's projections into the design process have certain limitations:

1) Answers may be binary, and analytical capability is limited to direct radiation and the effects of shading devices.
2) Most existing tools are based on incident solar radaition, and not transmtted energy.

Despite these limitations, this method appears prominently in academia, offering advantages such as simple and straightforward design interpretations, while also illustrating the relationship between a building's façade and solar radiation in a single picture. To overcome the limitations of this approach, multi-layer design tools developed from the original Mazria sunpath diagram are introduced in the following section. These new charts contain the total radiation received on a façade, as well as the total solar transmittance, or g-value (Karlsson & Roos, 2000), which is a solar angle-dependent feature.

To calcute the total radiation intensity (I), the intensity of solar radiation (I_b) on a window surface can be calculated from the intensity of direct radiation (I_{DNI}).

$$I = I_b + I_d + I_r \tag{1}$$

(I_b=Beam component, I_d=Diffuse component, I_r=Ground reflected component)

$$I_d = I_{DHI} * Y \tag{2}$$

(I_{DHI}=Diffuse horizontal irradiation, Y=Diffuse sky model)

where $Y$is determined after comparing 9 differnet models including Liu andJordan model (1963), Koronakis model (1986), Tian model (2001) and HDKR (2006).

$$I_r = (I_{DNI} * \sin\beta + I_{DHI})\varrho_g * \frac{1+\cos\beta}{2} \tag{3}$$

(β=Solar altitude, ϱ_g =Ground-reflectance)

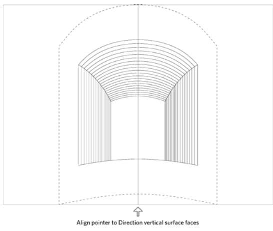
$$I_b = I_{DNI} * \mathrm{G}\cos\theta \tag{4}$$

(I_{DNI} = Direct normal radiation, θ = Incident angle)

where $\mathrm{G}\cos\theta$ is the cosine weighted g-value at incident θ. This value can be used to estimate solar gain in a builidng due to direct radiation (Dubois, 2000).

Multiple layers of a sunpath

Once a sunpath is drawn on the orthographic plane, lists of different values can be overlapped on top of the Mazria diagram. For example, simple shading masks, outlines of surroundings, and direct solar radiation charts are available for use with Mazria sunpaths to evalute the maximum shading depth and shapes. *Figures 2* and *3* illustrate two example layers that consider the building envelope and annual radiation on a facade.



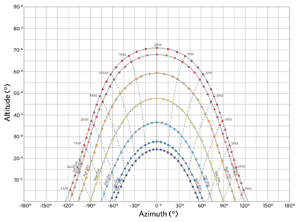


Figure 2 2D projection of window and shadings. *Figure 3 2D chart with annual solar radiation.*

However, the proposed sun chart consists of multiple layers such as radiation with incidence angle, radiation with window transmittance, and date-time occupancy schedule, all of which could be building energy consumption estimators. In the next section, the calculation methods for various solar estimators and their implementations are introduced in terms of their funtionality and the need for passive building design (Sriram, 2007).

Implementation

Outline of the software

The proposed tool is called the Environmentally driven Design Decision-making Tool (*Eabbit 1.0*); it includes functions for climate information, solar data, and statistical and visual analyses. *Eabbit 1.0* was developed to provide a comprehensive environmental framework. In this proposed tool's actual evolution, C# and Python 3 were used for functional development and statistical analysis, respectively. The main development in Grasshopper was accomplished by using a C# script, supporting Rhinoceros' common API to enhance computational efficiency. Due to the limited capacity of statistical analysis and drawing functions in Python for Grasshopper, the main statistical analysis functions were written in Python 3, using several libraries. All of the functions and codes were run or integrated into the *Eabbit 1.0* software and imbedded in Grasshopper to allow for analysis of the results of the integrated platform, as illustrated in *Figure 4*.

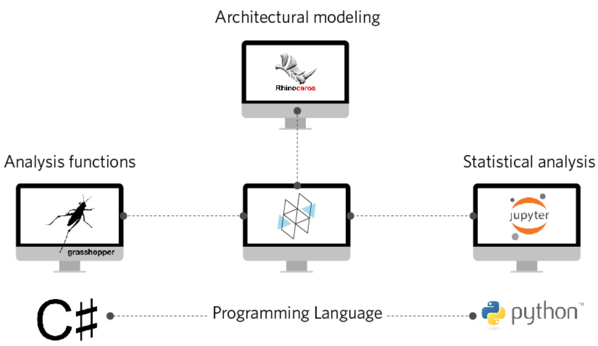


Figure 4 Programming language and packages used.

Development of the software

In its current form, *Eabbit 1.0* consists of five main components, with each sub-category demonstrating the comprehensive workflow of the software in its ultimate incarnation. These main categories consist of data management, data analysis, and fundamental calculations and design decision support.

For data management, it is desirable to be able to import and download the weather file for a specific location. Because on many platforms the conventional BPS weather file is a TMY3-based EPW file, *Eabbit 1.0* takes the EPW file format as the default for weather files. To generate a locally morphed sky model, the radiation values from EPW of NSRDB are adopted and translated. Throughout this process, the work focuses on determining the optimal weather information with contextual considerations in order to incorporate higher spatial and temporal resolutions of the solar radiation data.

By taking the EPW format of the weather file and manipulated sky model, a simple statistical analysis can be used to generate important charts and evaluation functions for climate-responsive designs. All of the weather statistics are shown in monthly/daily/hourly resolution, and users are able to selectively choose information important to their graphical analysis. Four 2D charts are available for flexible information delivery; these include a line graph, bar chart, and radar chart for general delivery the of local climate (see *Figure 5*).

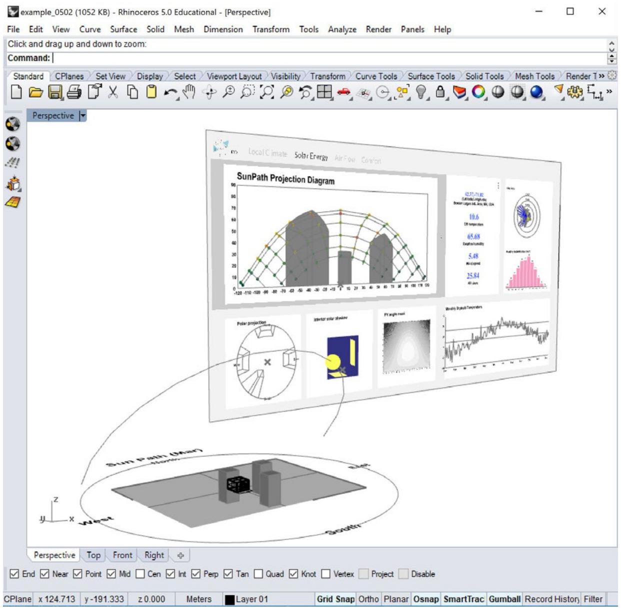


Figure 5 Component for evaluating statistics on the main analysis panel with modeling interface.

Importantly, *Eabbit 1.0* equips a weather file morphing function proposing a fitted sky model and radiation information during the design process. To customize this process on the tool, nine different diffuse irradiance models and three clear sky models are implemented and evaluated. The function automatically minimizes loss functions by calculating global radiation on the facades.

The 3D sunpath diagram has the capacity to support the analysis of interactive environments with information on the contextual buildings and building geometry. The 3D sunpath component can be used to conduct parametric studies with sun vectors and locations for specific days or periods. The proposed sunpath contains simplified information regarding the annual sun energy; this is important for utilizing building design attributes and passive design strategies. Both sunpaths have connectivity to the analysis functions and charts, and the results can be saved.

The calculated sun vector and position from the previous component is useful for analyzing the next components, which are radiation and shadow. The interface supports the real-time visualization of shadow drop-down on the ground plane, as well as in the interior space (see *Figure 7*). A contextual shadow study allows designers to evaluate the shaded properties of a façade to create openings for comfortable daylighting conditions, passive solar heating, and views to the outside. To determine the critical seasons and their average values, one must first calculate the heating and cooling degree days.

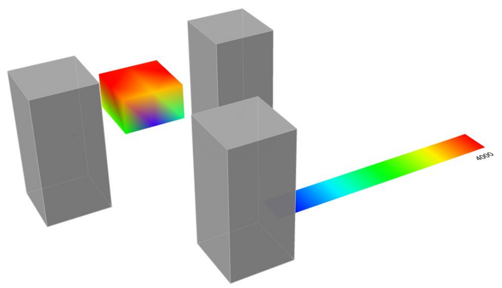


Figure 6 Mesh-radiation analysis (Falsecolor).

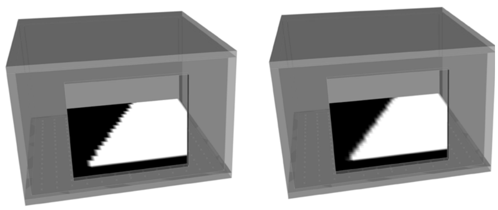


Figure 7 Shadow map before anti-aliasing (left) and after PCF (right).

The visualization options include both falsecolor (see *Figure 6*) and black and white maps (see *Figure 7*); hence, designers are able to select colored mesh options for their analysis results. To make the mesh colorization process efficient, a local grid of the sub-surface is converted into a mesh grid, with the updated sun position in the modelling time calculated directly in the current viewport. To reduce noise, percentage-closer filtering (PCF) is used to get fewer jaggies on the edges by calculating the percentage of the surface that is closer to the light and, therefore, not in shadow (Bunnell, 2007).

However, the 3D visualization method is not so effective as to alone allow designers to finalize their designs. Therefore, 2D functional diagrams are required to specify annual radiation intensity, materials properties, and so on (see the Methodology section above). The new feature was added to the existing *Eabbit 1.0* as a form of 2D mask (explained in the previous section). The final component is a 2D sun mask with the same information as the 3D sunpath, but more intuitive and designer-friendly during early design exploration.

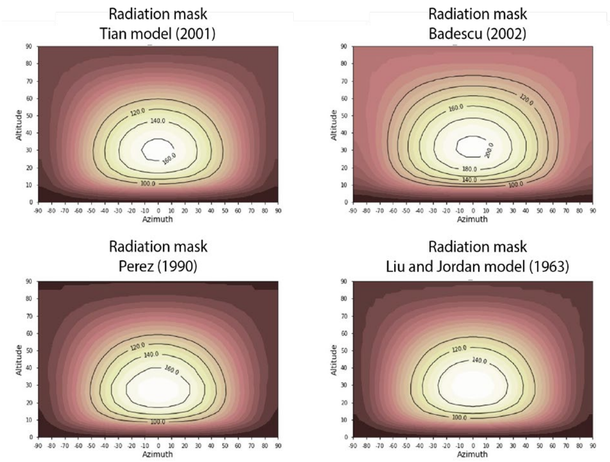


Figure 9 Radiation mask with different sky models.

The final component provides a visual diagram of the radiation intensity calculated on the vertical façade.

Figure 9 illustrates the radiation masks with different sky models implemented in *Eabbit 1.0*. To overcome the drawbacks of conventional suncharts (such as direct solar radiation maps), an added layer for solar radiation considers window transmittance values and occupancy

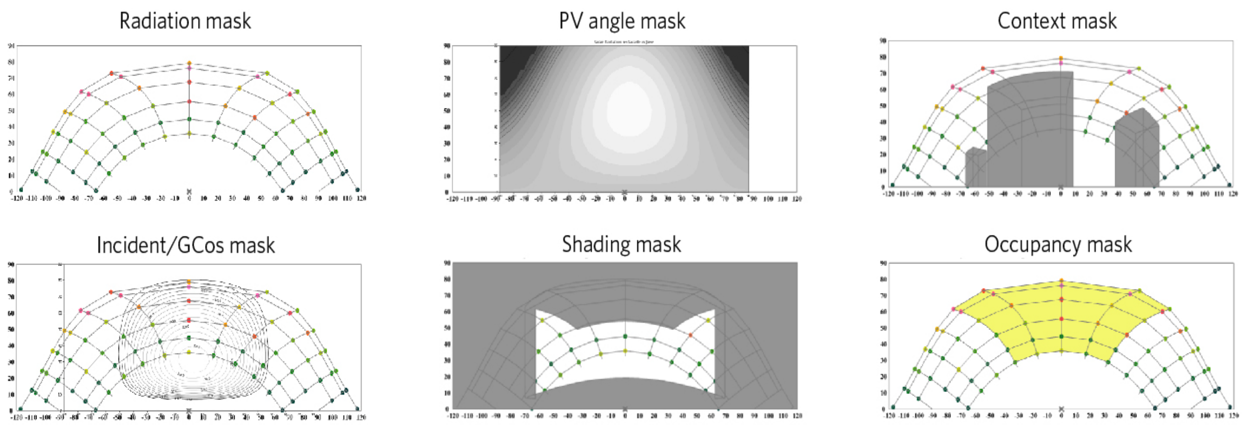


Figure 8 Components of the 2D diagram's layers.

schedules and offers the capacity to consider multiple factors at the same time. When users decide to review the values of certain properties, one of these six masks (see *Figure 8*) can be overlaid on top of the Mazria sunpath; the user has control over which masks are shown. Simultaneously, the color of the basic radiation mask varies based on additional information provided by the selected mask. If designers select multiple masks, the added values are weighted on top of the total radiation mask. Six masks are provided in the interface, each with the flexibility to overlap. These masks help to make certain choices related to window size, length, position, and material of the windows more efficient.

In terms of interface layout, the 2D sunchart can be shown together with the original building models, or be detached from the main panel and positioned separately on the modelling viewport (see *Figure 10*). Both options increase flexibility and usability, considering the interactive design and modelling process.

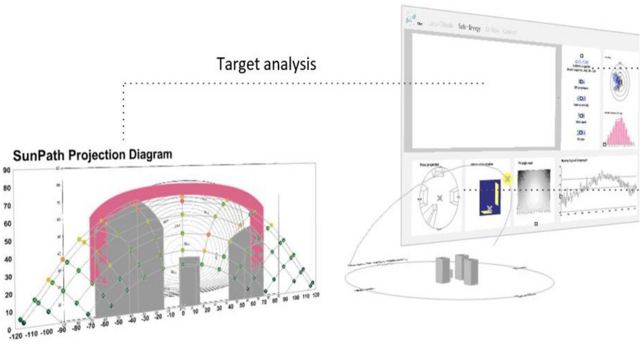


Figure 10 Interface layout with 2D sunchart.

A 3D sunchart offers various views and rich solar information, utilizing a sun globe to illustrate the annual path of the sun. However, the location of the sun and its angle are sometimes insufficient to evaluate the impact of solar energy on buildings. Notably, the total radiation received on a surface is not intuitively supported by a 3D sunpath. A weather file and physical equations allow us to calculate the radiation intensity on a façade by the month, day, and hour, as well as determine the annual average.

An orthographical sunpath is useful because it contains relevant sun information that cannot be included in a 3D sunpath. If the proposed software provides the functionality of a 2D sunpath on top of the 3D information, designers' benefits will be maximized during the design decision-making process.

The following hypotheses were explored:

- H1: Compared to a 3D-only interface, an interface including a 2D radiation mask will offer architects more information for design shading devices, thus reducing the annual heating and cooling energy use intensity (EUI) of the buildings designed.

- H2: Compared to a 3D-only interface, an interface including a 2D PV mask will offer direct information regarding the optimized PV tilt angle, resulting in more energy production from the PV array.

User Experiment

The usefulness of 2D sunpaths in a 3D modelling environment was evaluated through a user study that followed methods commonly employed in the field of Human-Computer Interaction (HCI). Each layer of sunchart was initially developed to support building fenestration and shading design. However, the effectiveness of multi-layer design support assistance had not yet been validated. The purpose of this study was to determine the effectiveness of the implemented sunchart in designing energy-efficient building façades.

1) Experiment setting

Two different versions of the interface were used in this study. One provided only a 3D sunpath (3D option, *Figure 11*) for a target building, and the other equipped a 2D sunpath (3D + 2D option, *Figure 11*) that contained the annual radiation exposure information and projected view of the target building and its surroundings. Users were asked to design simple elements such as shading devices and photovoltaic panels, with information related to the sun given for the different options. Later, the results of the each design option were evaluated by running energy performance simulations. Since energy consumption level was the final metric for evaluating the design performance of each option; climate information was a significant impact factor.

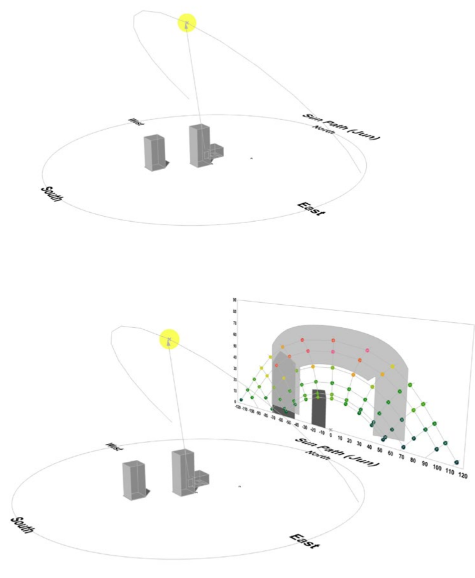


Figure 11 Experiment design 3D (up) and 3D+2D (down) options.

Therefore, two distinct climate conditions with different sunpaths were given for the same building. This was because dissimilar suncharts would result in diverse designs of building attributes. As can be seen in *Figures 12* and *13*, different climate zones demonstrate varying radiation maps when projected onto 2D image planes. For example, the average height of the sun is higher in LA than in Boston; the average intensity in June is also higher. The amount of radiation a building takes is closely related to its external radiation intensity throughout the year. Therefore, Option 3D and Option 3D + 2D had two different conditions in distinct climate zones.

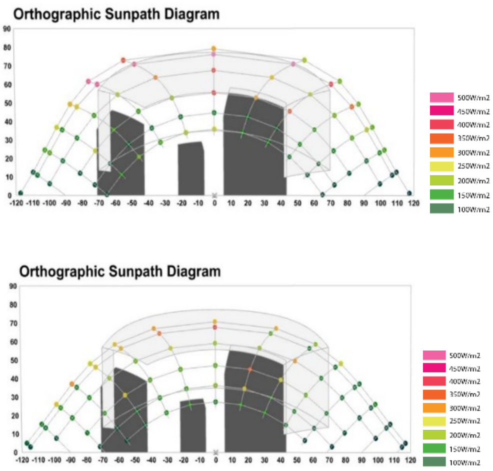


Figure 12 2D sunpath for Los Angeles (up) and for Boston (down).

In *Figures 12*, the annual radiation intensity map was provided on top of the orthographical radiation map in order to guide the design of the photovoltaics (PVs). *Figure 13* served as a guideline for determining the optimized tilt angle for the PV panels. The different levels of annual radiation intensity were mapped and represented with different color schemes. For example, the highest annual solar intensity is light yellow, and the lowest intensity is dark brown. Theoretically, then, if the PV panels are tilted to the same angle as the highest intensity map indicates, the largest annual electricity output should be produced.

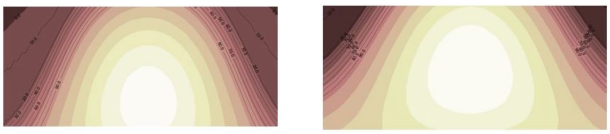


Figure 13 PV mask for LA (left) and Boston (right).

2) Participants

The target users were limited to architects and sustainability consultants, the potential future users of *Eabbit 1.0* mainly at the Harvard Graduate School of Design (GSD). Therefore, the demographics of the participants were limited to individuals with relevant knowledge of and experience with environmental design. In cases where the subjects were unfamiliar with the task required in the experiment, a brief introduction to the design goal for each option was offered. A total of 20 individuals participated. The group included 13 architects and seven sustainability designers; their experience regarding sustainable building design varied from one to ten years.

3) Experiment process

The experiment included two main parts: the user experiment regarding the architectural design decisionmaking process, and the post-experiment survey. The first part (approximately 15 to 30 minutes) involved designing building attributes for four different design scenarios situated in LA and Boston, with and without a 2D sunchart. The post-experiment survey collected personal perceptions of the effects of different sunpaths on the users' designs.

Once the sunpath and weather information were provided for both climate conditions (i.e., LA and Boston), each user designed a shading device based on the given solar information, first using Option 3D (i.e., only the 3D sunchart) and then using Option 3D+2D (i.e., with the 2D layer added). The test features of the target building included the lengths of the external shading devices, both horizontal and vertical (see *Figure 14*), and the angle of inclination of the PV panels. All had an impact on energy consumption and production.

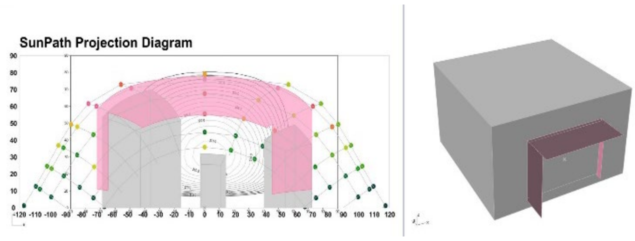


Figure 14 Shading design experiment setup.

The goal of designing the shading and PV panels was transparent to the participants; they were instructed to design a given building's shading devices in such a way that the annual energy consumption of the building decreased, especially for heating and cooling, without feedback from a building energy simulation. A second goal was to set the tilt angle of the PVs to maximize energy production at the specific site, with no simulation support.

Participants were first given Option 3D, LA, and then asked to design their buildings. They next turned to Option 3D+2D, a layer for LA, directly after using Option 3D. Then the participants adjusted their designs based on the additional information in the 2D sunchart and radiation intensity map. After the participants repeated this process for the Boston case, the post-experiment survey was distributed.

4) Results analysis

After collecting the results of the individual experiments from all of the participants, building energy simulations were done separately to compare the energy consumption levels of the buildings. Archsim (Dogan, 2013) for Grasshopper was used to calculate the annual heating and cooling EUI. Archsim is a parametric energy simulation software package that mainly utilizes the algorithm from EnergyPlus. *Table 1* shows the average EUI for each design option. The average cooling load in LA and both the heating and cooling loads for Boston were lowered. The value of the EUI reduction was meaningful in that it decreased in both settings, but it was not statistically significant (LA: $F(1,19)=0.011$, $p=0.65$, Boston: $F(1,19)=0.045$, $p=0.37$). In sum, a total of 0.15 kWh/m^2 in annual EUI was reduced for LA, and 0.442 kWh/m^2 was reduced for Boston.

Table 1 EUI Comparison

	3D_LA	3D+2D LA	3D_Boston	3D+2D Boston
Cooling (kwh/m2)	110.19	109.99	75.01	74.74
Heating (kwh/m2)	5.52	5.58	190.86	190.69
Total EUI (kwh/m2)	115.71	115.56	265.87	265.43

The total energy production for each design option was then calculated. The average energy production for both options increased by 4.9% and 4.8% for LA and Boston, respectively. The value of the annual energy production was meaningful in that it increased in both settings, and it was statistically significant (LA $F(1,18)=0.684$, $p=0.0025$, Boston $F(1,18)=0.364$, $p=0.0196$). This meant that that the PV designs for both climates worked considerably better, rejecting the null hypothesis.

Since the experiment used a small-scale building model with a 10m x 10m open floorplan, the total amount of energy consumption was not substantial, and was difficult to control through the operation of a single shading device facing south. The size of the south-facing window was 6m in width and 4m in height. Despite all of the constraints and limitations, an overall trend in the reduction of energy use was visible. *Figure 15* shows the average lengths of all shading options for each experimental condition.

An additional repeated measures ANOVA was conducted in which we added a new between-subjects variable to model participant expertise. The expertise was modeled as having two levels: novice (those with less than two years of exposure to environmental science and building physics), and expert (those with more than two years of relevant experience).

There was no significant interaction effect between expertise and the option with respect to PV energy production (LA $F(1,18)=00014$, $p=0.874$, Boston $F(1,18)=0.0206$, $p=0.888$). However, we observed a significant interaction effect between participant expertise and option in terms of LA ($F(1,18)=0.27$, $p=0.042$). This effect was nearly significant for Boston, as well ($F(1,18)=0.19$, $p=0.078$). The significant interaction effect meant that the experts and novices were differently affected by the two interface variants.

As illustrated in *Figure 16*, when presented with the 2D sunpath overlays, the expert group designed building attributes in ways that increased building energy consumption, while the novice group's designs decreased energy use throughout the year. These results suggest that people in the expert group did not refer to the information provided by the software, and instead trusted their own background knowledge. Unlike the expert group, the novice group tended to design building devices in response to the information given. This is likely what yielded the differing results between the two groups.

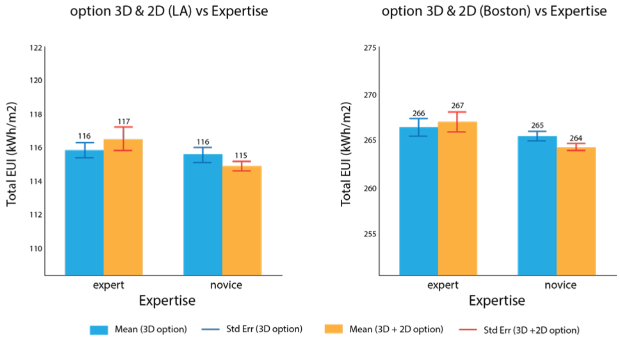


Figure 16 Results comparison by level of expertise.

The usefulness of the 2D graphics in designing PVs was apparent (see *Figure 17*). Almost all of the participants referred to the values provided in the 2D chart, and the optimized values on the graph indicated the highest energy production throughout the year. It is clear, then, that use of a 2D chart in PV design is highly effective.

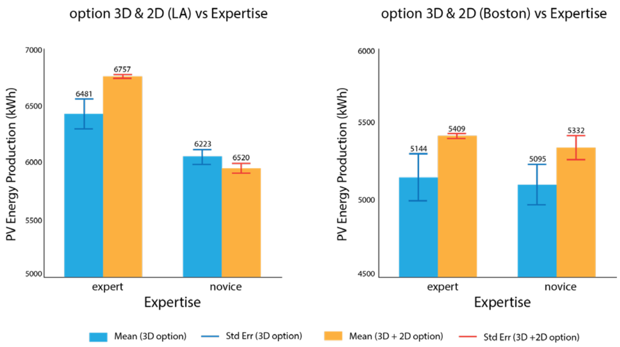
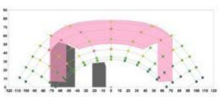
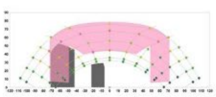
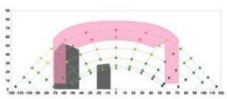
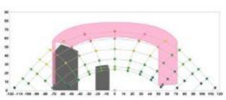


Figure 17 PV angle by level of expertise.

5) Post-experiment survey

The results of the post-experiment survey illustrated users' preference for the 2D mask when creating their PV

	option1_LA	option2_LA	option1_Boston	option2_Boston
UP (p 0.7 / 0.97)	2.94	3.595	2.165	2.175
EAST (p 0.53 / 0.52)	1.325	1.595	0.85	0.25
WEST (p 0.23 / 0.95)	1.095	1.53	1.02	1.245

Figure 15 Lengths of the final shading devices for each option.

designs (see *Figure 18*). Overall, for building and shading designs, users preferred to have both the 2D and 3D sunpaths available during the analysis process.

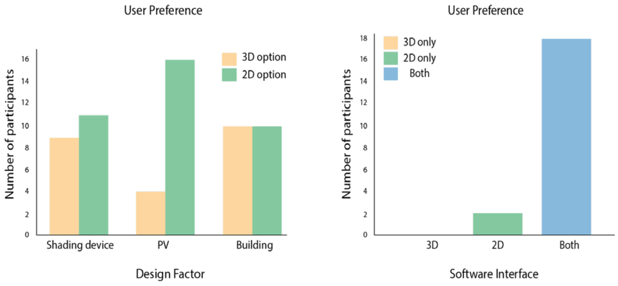


Figure 18 Results of the post-experiment survey.

Several suggestions for further improving *Eabbit* emerged from the comments submitted:

- Designers need more simplified tools with optimal solutions.
- Instant feedback and limited options are necessary.
- The 3D sunpath is meaningful but requires average values and data for critical seasons, rather than date-time data.
- A more interactive GUI is required; for instance, it would be helpful if by clicking on the radiation circle, a user could see the declination angle for that season or hour of the day.
- Further connectivity to calculate simple energy loads might be useful.

Conclusion

The integration of building performance simulations (BPS) during the early design phase is one possible way of encouraging designers to participate actively in energy-efficient design. However, this requires a high level of expertise and is both computationally expensive and labor-intensive; moreover, the relevant tools are not currently available in a simple modelling interface.

This research shows the workflow and feasibility of the Environmental Analysis (EA) method and proposed sunchart implemented in *Eabbit 1.0*. Comprehensive visual representation methods were compared, taking solar energy as the basis for prototype development. *Eabbit 1.0* provides a wide range of design potential, due to the application of an advanced EA method early on in the design process. Furthermore, a usability assessment of *Eabbit 1.0* was done, leading to discussions regarding utilizing different representation methods in BPS software.

The user experiment showed the effectiveness of employing 2D masks in design, combined with simplified 3D sunpaths.

Limitations of the user experiments were as follows:

- Due to the limited experiment time and demographics of the sample, only a few of the proposed 2D masks were evaluated in the design of passive buildings.
- The number of users should be increased.

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