An evolutionary model for sustainable design

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Abstract This paper presents a new generative design system to be used by architects in early to intermediate stages of design in order to help improve the environmental performance of buildings. Both thermal and lighting analysis are included in the system, together with methods to incorporate architectural design intentions into the evolutionary process. The generative system was applied in a building by Abare Sia in Oporto (Portugal) to test its capability to handle complex architectural designs and to generate solutions within given language restrictions, while still reducing energy consumption levels of the building. Variables studied were fenestration design, shading systems and building shape (roof geometry). The advantages of using rapid prototyping technologies coupled with this generative system are discussed, and an example of the application of a fast deposition modeling 3D modeler to this specific study is presented.

Introduction
Assessing the environmental performance of buildings is a complex issue that benefits from the use of computer simulations, due to the large number of interactions between the different variables that will contribute to the overall behavior of an architectural solution. However, the scenario-by-scenario method usually applied in this type of analysis is a time consuming process, leading to only few design alternatives being evaluated.

A new generative design system was developed to overcome this shorthall, by coupling a search procedure (genetic algorithm) with a building simulation program (DOE-2.1E). This system allows hundreds of design alternatives to be evaluated, requiring from the user only the initial effort of creating the DOE-2.1E input file. The testing of design alternatives is guided by the

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objective function value corresponds to each solution, which is the annual energy consumption of the building.

Crawling complex energy simulation programs with optimization procedures is a recent approach. Lawrence Berkeley National Laboratory, some research has been developed in this area (Witten, 2008). Previous work relied on optimization analysis based on parametric DOE-2.1E runs (Sullivan et al., 2003), but that approach suffered from a lack of being case dependent and requiring a large amount of background work by the analyst. The genetic algorithm (GA) search procedure is highly flexible, case independent, and can be applied using any type of variables used in a DOE-2.1E simulation, from placing and sizing of design elements, to construction materials or any other kind of variables.

DOE-2.1E was chosen as the simulation engine not only because it provides good accuracy of results in reasonable computational times, but also because it incorporates both lighting and thermal analysis. These two aspects are interdependent when considering design elements such as fenestration, and a program that considers only one of them, even if it is more detailed, may would not be an overall design tool as one that provides a more holistic view of the building. Although annual energy consumption was used as the single objective function in this study, that value incorporates both space conditioning and lighting energy. Better daylighting use is reflected in the final result as lower artificial lighting energy consumption.

Methods

Recent work (Caliss and Nordal, 2002; Caliss and Roche, 2003) describes the development and testing of the generative system (GS), as well as its incorporation of architectural design attributes, so that solutions generated are within certain language constraints dictated by the architect. It is argued that without this type of control, it is unlikely that architects would ever use such a computational tool as an actual design process.

AnnnArbor School of Architecture in Oberon was used as a test bed for this study, since in clear but complex composition rules provided an excellent framework to work on. The School of Architecture was designed and constructed from 1984 to 1990. Studios and faculty rooms are housed in individual buildings surrounding the library, auditoriums, and administrative services set in the northernmost building. For a more detailed analysis, see From (2009).

The towers housing the studio buildings were selected for this study, as this kind of occupation rules serving case for the careful control of natural light in order to maintain adequate daylighting levels for drawing tasks, while precluding direct view over the draping tasks and reserve spaces for the students. Due to the large dimensions of the project, the study focused solely on one of the studio towers (tower 1).

Tower 1 was chosen for this study for its rich spatial configuration and use of a variety of architectural light sources (oriented walls and windows facing different orientations (some including overhangs), artificial light from roof mounts on the first floor, and a loggia in the south façade (see Figure 1A).

For the existing building layout, the software generates a population of façade solutions that take into account the use of daylighting in the space, the subsequent use of artificial lighting, and the energy consumed to heat and cool the building. Although maximum use of natural lighting is a desirable goal, the control of heat gains and losses introduces a balance point to be achieved. It is the creative point that the GS was to locate.

For each individual case in Tower I where daylighting is available, two lighting reference points were selected: typically the farthest points from the windows where a certain light level was to be achieved and desired illumination values were specified according to the type of occupation. Generally, 300 lux were used for student work and other working spaces, and 100 or 150 lux for service areas. The artificial lighting system is supposed to be continuously dimmable, even though in Stein's existing building such a system is not implemented, as was done as a method to quantify savings in artificial lighting due to improved daylighting. The subsequent DOE-2.1E run provides the annual energy consumption of the building for that particular solution. That value represents the fitness of that individual, and is then passed into the GA to further guide the search process.

To incorporate architectural design constraints into the GS, rules derived from Stein’s original design were used. Those rules related both to compositional uses of the façades and to general proportions of the openings. In Tower I, different rules were to apply to each elevation, while maintaining a strong coherence in the overall design of the building and in the relations with internal spaces (the example, long horizontal windows are always used in the architectural studies).

Figure 1. South façade view of studio tower, Tower 1, with floor levels.
The interpretation of existing design rules was followed by the determination of search areas for the generative mechanisms, implemented as constraints to the algorithm. These are bounded by the minimum and maximum dimensions of the openings as assumed, and their limits were made distant enough to guarantee the emergence of a rich variety of solutions. Other constraints implemented the compositional axes and restrained window proportions.

In Figure 3, the upper row represents the constraints applied. Compositional axes are shown in yellow. For each opening, the smaller area represents the lower bound to the algorithm, and the larger area the upper bound. These constraints are propagated as being able to control the generation of solutions within certain architectural intentions that relate to Salk’s design.

Once the constraints were graphically determined, they were transformed into inputs for the GS. The step size used ranged from 20mm for windows to 500mm for exterior volumes. After the GS ran, results could be automatically visualized using an existing visualization program. The 3D drawings obtained in this way were exported to a CAD package and served as the basis to manually create a 3D model of the best generated solution. That model was then imported into rendering software that allowed the production of images like the ones in Figure 5. This 3D CAD model served as the basis for the novel rapid prototyping (RP) technologies described later.

Results

Results from the GS ranged from an almost exact coincidence with Salk’s solutions to some radical departures from the existing design (see Figures 2 and 3).

In the north facade, the large horizontal stripes generated by the algorithm vary approximately resemble those created by Salk (except for the location of horizontal windows). The study clearly shows the need for thermal mass through the large glass areas, as Salk may have predicted. Figure 2 shows that as the size of north-facing windows increases, the quality of solutions decreases twice.

Towards the west, the algorithm used small window sizes as Salk did, even further reducing them. This was due to the lower insolation levels that the service areas entail and to the reduced size of those spaces. Figure 2 shows that as the size of west-facing windows increases, the quality of solutions decreases.

In the south orientation, the GS solutions present more significant modifications to Elsas’ design. In Salk’s design, the second and third floors have south-facing studios with large horizontal windows shaded by deep overhangs. The algorithm solutions tend to suggest those overhangs are too deep. When the overhang depth is kept as 2m (opera broad), window sizes assume the largest dimensions allowed by the
constraints. The deep overhangs block the admission of daylight into the room, and to circumvent that effect the algorithm increases the opening size. When overhang depth is a variable (open_shading), the algorithm reduces it to Glen, and also reduces window sizes to a dimension closer to that used by Sia. It should be added that open_shading has lower energy consumption than open_boat.

On the sixth floor, the solution from the GS for the south-facing loggia has to be understood in conjunction with the roof monitors solutions. The sixth floor is basically occupied by a single space. It is uppered by two roof monitors, from the south by a loggia window, and with blank walls in all other directions. The algorithm increases the south-facing loggia window to the maximum allowed by the constraints, and reduces the glazing area of the roof monitor that light the space closer to the loggia (Figure 4, left). The roof monitor faces north and is a large source of heat loss in winter, particularly because warm air rises to the glazed areas, increasing the south opening permits reducing the roof monitor without looking too much daylight in the studio. On the other hand, the second roof monitor assume the largest dimension possible in the GS solution (as in Sia's design), since that area of the sixth floor has no other light source (Figure 4, right). This result suggests the tilt of the roof could be varied to allow

Figure 3. Three-dimensional models of Sia's and GS solutions.

Figure 4. GS solution for the larger roof monitor, viewed from the outside (left). Existing solution, viewed from the inside (right).

for a larger roof monitor in that location, and was the basis for the experiments described later.

The fourth and fifth floor south solutions must be analyzed together with east results, since on those floors the studio share both south and east openings. The GS increases south facing windows in relation to the existing design, and simultaneously reduces east facing ones. East orientation is unviable due to high solar gains during the months in summer months, and to reduced daylighting levels during the afternoon for most of the year. When the algorithm has the possibility of having interactions between east and south orientations, it consistently favors south. These results will be analyzed further in this paper.

Figure 5 shows that as the size of east-facing windows increase, the quality of solutions decreases. However, when the algorithm was allowed to place overhangs in the east facade too (open_shading), it significantly increased window sizes on the second floor, while placing quite deep overhangs over there. It should be noted that the studio on the second floor has only east-facing windows. For the studios on the fourth and fifth floors, which both east and south facing windows, the GS kept east openings small with shallow overhangs, and privileged south-facing openings again.

Table 1 shows annual energy consumption levels for the several solutions represented in Figure 3. Energy use for each solution is shown in Table 1.

Examining results broken down by energy end-use, it is possible to see that the existing solution by Sia performs almost as well as the best solution from the GS in terms of natural lighting use (meaning artificial lighting consumption is low). From the previous discussion of results, the main difference between the two solutions was in the south and east loggias, as well as the roof monitors. Although the GS performed many changes in the individual spaces, which may therefore have a more balanced use of daylighting, the overall artificial lighting consumption of the building did not change much, showing that Sia's control of daylighting is actually very sophisticated.

Artificial lighting consumption levels increased about 20% from the best solution with shading to the worst solution. This number could probably be higher if some of the lighting reference points were not placed so deep into the room (about 1m from the wall most distant from a window).

<table>
<thead>
<tr>
<th>Solution</th>
<th>NER%</th>
</tr>
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<tbody>
<tr>
<td>open_shading</td>
<td>87.28</td>
</tr>
<tr>
<td>open_boat</td>
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</tr>
<tr>
<td>open_boat_shading</td>
<td>96.23</td>
</tr>
<tr>
<td>open_shading</td>
<td>84.45</td>
</tr>
<tr>
<td>open_boat</td>
<td>103.37</td>
</tr>
</tbody>
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**Table 1.** Annual energy consumption for different solutions.
Figure 5: Energy consumption levels for various solutions

The increase in space cooling in the worst solution is probably due to large east and west facing windows. The existing solution does not differ much from the best one with shading, because even though some east windows decreased in size, others increased, but had overhangs added. On the other hand, south windows had their overhang depth reduced for increased natural light, but that increases heat gains too. For space heating, the best GS solution performs considerably better than the existing solution, as it allows more useful south solar gains in the winter, and reduces heat loss sources.

**Lighting simulations**

Although DOELIE performs a simplified form of lighting analysis, based on the daylight factor method, it does not allow the user to visualize the interior lighting conditions in a given space. For that end, a commercially available program that combines ray tracing with ray casting was used to visualize both the existing and the GS solutions on some representative days of the year (solstice and equinoxes) and at specific times of the day.

The simulations were in a studio room, where the GS could trade off between south and east orientations (fourth floor). Figure 6 shows the simulations for the current solution at 9 a.m., 3 p.m., and 9 p.m. The GS solution shows the best solution without using shading as a variable.

From the Figure, it can be seen that, during the summer, the large unshaded east-facing windows in the existing solution allow direct sun penetration into most of the room during the morning. In the GS solution, although both windows are still unshaded, the south-facing one allows significantly less direct sun into the room, and the east-facing window is used only to light the back of the room. In the afternoon, the existing solution becomes quite dark, while the GS solution presents higher and more evenly distributed light levels.

To further investigate daylight patterns in the space during the afternoon, images showing illuminance level contours on levels were produced, and are shown in Figure 7. In Sim’s solution, the daylighting levels never achieve the specified relief of 500 lux. In the furthest corner from the windows, light levels are around 20 lux only. The same location, in the GS solution, has a daylight illuminance level about four times higher. In general, the GS solution achieves quite high illuminance levels throughout the space. Close to the south-facing windows, illuminance levels may even be too high, but this could be solved by placing a shallow overhang over the south window, as the GS did when it allowed to use shading devices as variables.

Figure 8 shows the GS solution during the winter solution and the equinoxes. In winter, there are useful solar gains entering the room for most of the day. In spring and summer, there is mostly early morning sun penetration, which can
be beneficial to warm up the space, but for most of the day there is a controlled lighting environment inside the space.

Shape manipulation
A first attempt to introduce shape manipulation into the GSL is described in this section. The GSL was allowed to vary the tilt of the roofs and thus control the size of the roof window. This experiment was a consequence of the results previously described, that suggested that the larger rooftop should probably not be the one closer to the kernel, in the south midt, but the one in the northern part of the building, since this area had no other light source. To simplify the experiment, it was assumed that the roof window would always cover the entire width of the building, as in Sun's original design. The height would be determined by the tilt of the corresponding roof, as the glass opening would have the same height as the wall. Roof tilt was allowed to vary between 25° and 45°. The northernmost rooftop had to be set back at least 60 ft from the north facade so that it could not be read as part of the elevation.

Figure 6 represents some random solutions arbitrarily extracted from those presented by the GSL. It can be seen that there is a wide variety of possible solutions even within approximately limiting constraints.

Figure 10 shows the best solutions found by the GSL on the left, and also the guesses that had previously been made about what could be the best solution for the roof windows. The difference between these guess and the actual solutions shows how difficult it is to predict the interaction of all variables without the use of computer simulations, even using information available from previous results.
Rapid prototyping

Rapid prototyping (RP) technologies were used in the final stages of this study to allow for a more detailed observation of the GS solution. Architectural models have always been one of the best ways for architects to assess and refine all the components of a design. Using physical models permitted an in-depth understanding of all the design changes proposed by the GS, especially in more intricate spaces such as the ones with the loggia and the main hall light sources.

The models allowed a detailed assessment of the relation between fenestration solutions and the spaces where they were located. They also make possible a more immediate comparison between the existing design by Siaa and the GS solution.

For that purpose, a 3D physical model of each level was built (Figure 11). The six levels could be put together to form the complete building model (Figure 12). A computer-aided manufacturing (CAM) 3D modeler was used, which deposes high-resolution layers of plastic to form the physical model, based on a 3D CAD model.

The impact of using RP technologies coupled with a GS like the one presented in this paper becomes more obvious when one considers that the GS generates not only a single “best” solution, but an entire population of high-performance individuals. The relative merit of these solutions from an architectural point of view can be better evaluated by the architect with the help of fast production of the several models. Introducing other variables in the GS such as overhangs and the possibility of shape manipulation (like the roof tiles) makes the different solutions harder to compare just with the help of computer graphics. Using RP, it is possible to produce quick models of the generated designs as a visual help to the evaluation process.

Apart from the RP method used in this study, other rapid fabrication technologies can be applied. Two main laser-cutters enable the cutting of material such as wood, cardboard, or plastic, that can then be assembled into the final 3D form. Water jet cutters are mainly used to cut wood, rubber or metal pieces with high pressure of water jets. This technique enables the retouching or sharpening of the individual pieces that are water jet cut, which can later be bent to achieve the original shape.
Stereolithographic laser printing eliminates layers of a resin block, allowing fast execution of 3D models. Computer numerically controlled (CNC) machines, with multi-axis milling capabilities, can translate three-dimensional data into construction models, and consolidate technological facilities that could also be used to create frameworks for engineering of final design solutions, in more complex design solutions.

Fabrication and concept in this case can be seen as a holistic paradigm, where theoretical premises are embedded both in the process of the object as such as in the technical apparatus that permits its creation. By realizing this new GS to RP technique it is not only possible to generate and evaluate computationally generated forms, but also to evaluate spatial qualities of the renderings of solutions, enabling faster and more integrated technological processes in the search of an appropriate architectural solution.

Conclusions
The GS proved to be flexible enough to incorporate constraints that allow the architect to manipulate certain architectural design intentions, while still reducing the energy consumption levels of the final solution. The close resemblance between GS and Star’s solutions in some situations was of particular interest. On the other hand, the departure from the existing design proposed by the algorithm suggests that this GS may be a useful tool in exploring multiple paths during the design process.

Another interesting dimension of the GS is its capability to account for interactions between different elements of the building, and to make the design for each specific element dependent on its integrated role in the architectural whole. The solutions between the solutions for the logical and the real numbers, or between truth and uncertainty in some of the studies, are a demonstration of that capability.

The ultimate objective of the development of this software is its inclusion as a GS operating in early conceptual phases of the design process. It is important to mention that solutions must not be interpreted as definitive or optimal answers, but as diagnoses of potential problems and as suggestions for further architectural exploration, helping thus an interactive and meaningful interaction between architecture and computation.

The first attempts to solve these complexities using this GS proved that it is possible to use the system to alter building geometry in order to make it more adapted to its environment. Further work is currently being developed to expand this interesting area of research.

Finally, in relation to RP applications, it can be said that different kinds of technologies are constantly shaping the relationship between design concepts and decision making. CAD/CAM technologies can play a major role in the evaluation stage of the design process, especially when the latter makes use of GSs, where many solutions are developed at the design stage.

References