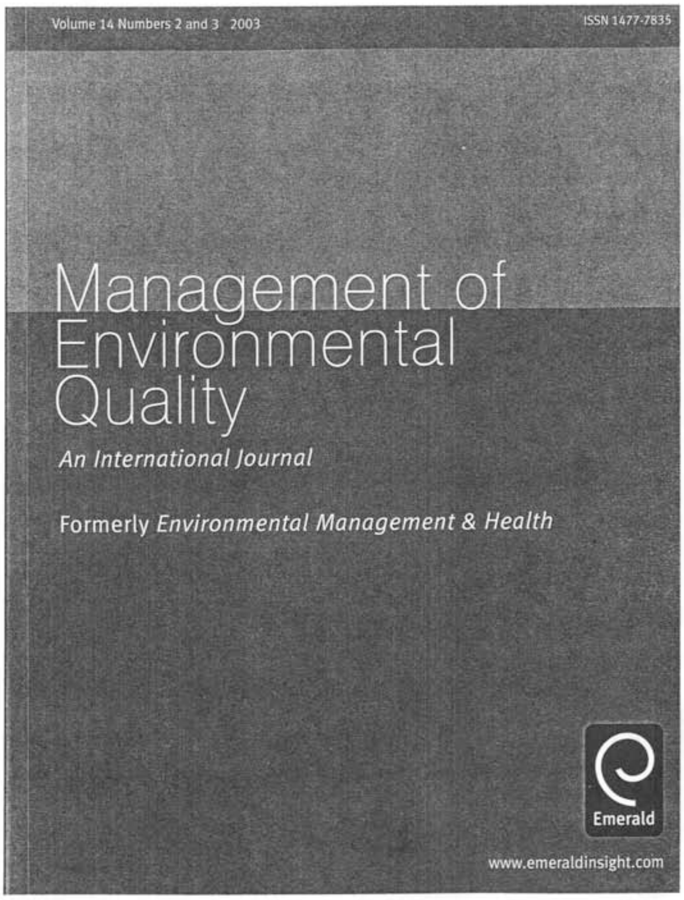


Volume 14 Numbers 2 and 3 2003
ISSN 1477-7835

Management of Environmental Quality

An International Journal

Formerly *Environmental Management & Health*

Emerald
www.emeraldinsight.com

The Emerald Research Register for this journal is available at
http://www.emeraldinsight.com/researchregister

The current issue and full text archive of this journal is available at
http://www.emeraldinsight.com/1477-7835.htm

An evolutionary model for sustainable design

Luisa Caldas
Technical University of Lisbon, Instituto Superior Técnico, Lisboa, Portugal
Leslie Norford
Massachusetts Institute of Technology, Building Technology Group, Cambridge, Massachusetts, USA, and
João Rocha
Massachusetts Institute of Technology, Design and Computation Group, Cambridge, Massachusetts, USA

Keywords *Genetic algorithms, Environmentally friendly, Rapid prototyping, Architecture*

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 to a building by Alvaro Siza 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 fuse 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 shortfall, 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

---

Luisa Caldas developed this work as part of her PhD dissertation in Architecture at Massachusetts Institute of Technology, with a grant from PRAXIS XXI program, Fundação para a Ciência e a Tecnologia, Portugal. João Rocha is also a PhD student in Architecture at Massachusetts Institute of Technology with a grant from PRAXIS XXI. They would like to thank William Mitchell, Álvaro Siza and Peter Testa for their kind support.

Management of Environmental Quality: An International Journal
Vol. 14 No. 3, 2003
pp. 383-397
© MCB UP Limited
1477-7835
DOI 10.1108/14777830310479450

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

Coupling complex energy simulation programs with optimization procedures is a recent approach. At Lawrence Berkeley National Laboratory, some research has been developed in this area (Wetter, 2000). Previous work relied on regression analysis based on parametric DOE-2.1E runs (Sullivan *et al.*, 1992), but that approach suffered mainly from 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 to 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.

DOE2-1E 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. Those two aspects are interdependent when considering design elements such as fenestration, and a program that considers only one of them, even if in a more detailed way, would not be as useful a design tool as one that provides a more holistic anaysis 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 (Caldas and Norford, 2002; Caldas and Rocha, 2001) describes the development and testing of the generative system (GS), as well as its incorporation of architectural design intentions, so that solutions generated are within certain language constraints defined by the architect. It is argued that without this type of control, it is unlikely that architects would ever use such a computational tool in an actual design process.

Álvaro Siza's School of Architecture at Oporto was used as a test bed for this study, since its clear but complex composition rules provided an excellent framework to work on. The School of Architecture was designed and constructed from 1984 to 1996. Studios and faculty rooms are housed in individual buildings (towers); the library, auditoriums and administrative services are in the northern-most buildings. For a more detailed analysis, see Testa (1999).

The towers housing the studio teaching rooms were selected for this study, as this kind of occupation makes a strong case for the careful control of natural light in order to maintain adequate daylighting levels for drawing tasks, while precluding direct sun over the drafting tables and excessive solar gains in the rooms. Due to the large dimension of the project, the study focused solely on one of the studio towers (tower H).

Tower H was chosen for this study for its rich spatial configurations and use of a variety of architectural light sources: fenestrations of different proportions and sizes facing distinct orientations (some including overhangs), zenithal light from roof monitors in the top floor, and a loggia in the south façade (see Figure 1).

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 this elusive point that the GS tries to locate.

For each individual space in Tower H where daylighting is available, two lighting reference points were selected (typically the furthest points from the windows where a certain light level was to be achieved) and desired illuminances values were specified according to the type of occupation. Generally, 500 lux were used for studios and other working spaces, and 300 or 150 lux for service areas. The artificial lighting system is supposed to be continuously dimmable, even though in Siza's existing building such a system is not implemented, as this worked 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 intentions into the GS, rules derived from Siza's original design were used. Those rules related both to compositional axes of the façades and to general proportions of the openings. In Tower H, different rules seem to apply to each elevation, while maintaining a strong coherence in the overall design of the building and in the relations with internal spaces (for example, long horizontal windows are always used in the architecture studios).

Note: Tower H is in the foreground

Figure 1.
Southeast view of studio towers. Tower H is in the foreground

The interpretation of existing design rules was followed by the determination of search areas for the generative mechanism, implemented as constraints to the algorithm. Those are bounded by the maximum and minimum dimensions the openings can assume, and their limits were made distant enough to promote the emergence of a rich variety of solutions. Other constraints implemented the compositional axes and restrained window proportions.

In Figure 2, the upper row represents the constraints applied. Compositional axes are shown in lighter lines. For each opening, the smaller area represents the lower bound to the algorithm, and the larger area the upper bound. These constraints are proposed as being able to control the generation of solutions within certain architectural intentions that we relate to Siza's design.

Once the constraints were graphically determined, they were transformed into inputs for the GS. The step size used ranged from 30cm for windows to 50cm for exterior shades. After the GS ran, results could be automatically visualized using an existing visualization program. The 2D 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 exported to rendering software that allowed the production of images like the ones in Figure 3. This 3D CAD model was also the basis for the use of rapid prototyping (RP) technologies described later.

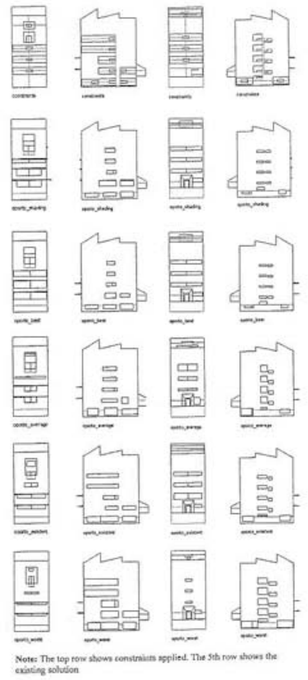
Results

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

In the north façade, the large horizontal stripes generated by the algorithm very approximately resemble those created by Siza (except for the melodic variations in height in the original design), denoting that in Oporto's mild climate the use of natural light in the studios clearly offsets the heat losses through the large glazing areas, as Siza may have predicted. Figure 2 shows that as the size of north-facing windows decreases, the quality of solutions decreases too.

Towards the west, the algorithm used small window sizes as Siza did, even further reducing them. This was due to the lower illuminance levels that the service areas (stairs and restrooms) require 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 in relation to the existent. In Siza's design, the second and third floors have south facing studios with long horizontal windows shaded by 2-meter deep overhangs. The algorithm solutions tend to suggest these overhangs may be too deep. When the overhang depth is kept as 2m (oporto_best), window sizes assume the largest dimensions allowed by the



Note: The top row shows constraints applied. The 5th row shows the existing solution

Figure 2.
Results for Oporto

constraints. The deep overhangs block the admittance of daylight into the room, and to counteract that effect the algorithm increases the opening size. When overhang depth is a variable (oporto_shading), the algorithm reduces it to 0.5m, and also reduces window sizes to a dimension closer to that used by Siza. It should be added that oporto_shading has lower energy consumption than oporto_best.

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, lit from above 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 glazed area of the roof monitor that lights 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 losing too much daylight in the studios. On the other hand, the second roof monitor assumes the largest dimensions possible in the GS solution (as in Siza'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 for a larger roof monitor in that location, and was the basis for the experiments described later.

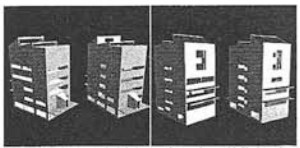


Figure 3.
Three-dimensional models of Siza's and GS solutions

Note: The two images on the left show north east views, with Siza's on the left and GS on the right. The two images on the right show south west views, with Siza's on the right and GS on the left

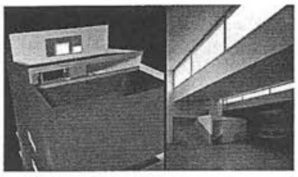


Figure 4.
GS solution for the larger roof monitor, viewed from the outside (left). Existing solution viewed from the inside (right)

The fourth and fifth floor south solutions must be analyzed together with east results, since on those floors the studios 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 unfavorable due to high solar gains during the morning in summer months, and to reduced daylighting levels during the afternoon for most of the year. When the algorithm has the possibility of trading between east and south orientations, it consistently favors south. These results will be analyzed further later in this paper.

Figure 2 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 façade too (oporto_shading), it significantly increased window sizes on the second floor, while placing quite deep overhangs over them. 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 have both east and south facing windows, the GS kept east openings small with shallow overhangs, and privileged south-facing openings again.

Table I shows annual energy consumption levels for the several solutions represented in Figure 2. Energy end use for each solution is shown in Figure 5.

Examining results broken down by energy end-use, it is possible to see that the existing solution by Siza performs almost as well as the best solution from the GS in terms of natural lighting use (meaning artificial light consumption is low). From the previous description of results, the main differences between the two solutions were in the south and east façades, 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 Siza's control of daylighting is actually very sophisticated.

Artificial lighting consumption levels increased about 22 per cent 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).

Solution	MWh
oporto_best_shading	87.58
oporto_best	89.99
oporto_average	96.22
oporto_existent	96.45
oporto_worst	110.55

Table I.
Annual energy consumption for different solutions

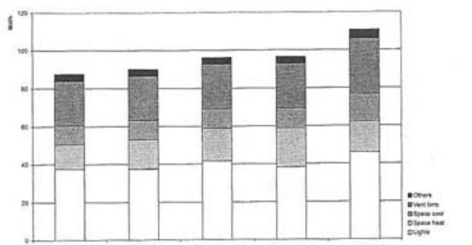


Figure 5.
Energy consumption levels for Oporto solutions

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 DOE-2.1E 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 radiosity with ray-tracing was used to visualize both the existing and the GS solution at some representative days of the year (solstices and equinoxes) and at specific times of the day.

The space simulated was a studio room, where the GS could trade off between south and east orientations (fourth floor). Figure 6 shows the renderings for the summer solstice at 9 a.m., 10 a.m., noon and 3 p.m. The GS solution shown is 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 in 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.

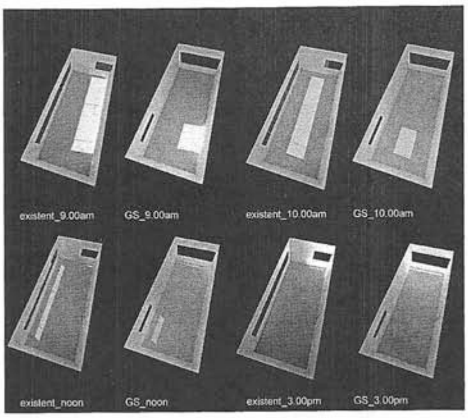


Figure 6.
Comparison of existing and GS solutions (summer solstice, 9 a.m., 10 a.m., noon and 3 p.m.)

To further investigate daylight patterns in the space during the afternoon, images showing illuminance level contours (in lux) were produced, and are shown in Figure 7. In Siza's solution, the daylighting levels never achieve the specified setpoint of 500 lux. In the furthest corner from the windows light levels are around 200 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 luminance 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 was allowed to use shading devices as variables.

Figure 8 shows the GS solution during the winter solstice and the equinoxes. In winter, there are useful solar gains entering the room for most of the day. In spring and autumn, there is mostly early morning sun penetration, which can

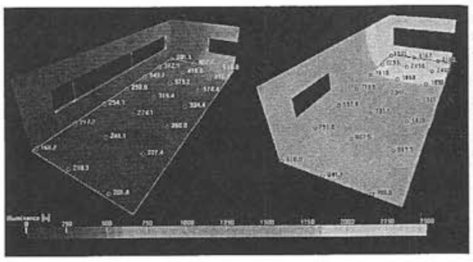


Figure 7.
Lighting levels contours for existent (left) and GS (right) solutions. Scale goes from 0 to 2500 lux

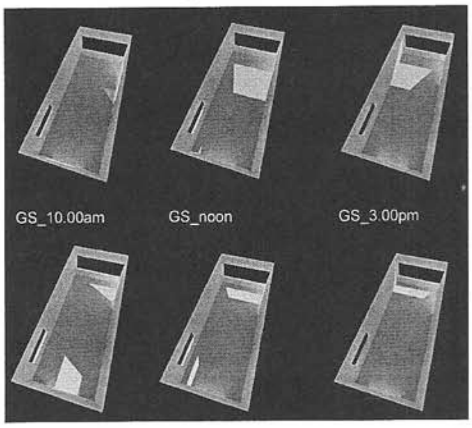


Figure 8.
Top row: GS solution during winter solstice; Bottom row: GS solution during equinoxes

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 GS is described in this section. The GS was allowed to vary the tilt of the roofs and thus control the size of the roof monitors. 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 loggia, in the south side, but the one in the northern part of the building, since that area had no other light sources. To simplify the experiments, it was assumed that the rooftop monitors would always cover the entire width of the building, as in Siza's original design. The height would be determined by the tilt of the corresponding roof, as the glazed opening would have the same height as the wall. Roof tilt was allowed to vary between 10° and 45°. The northern-most rooftop had to be set back at least 2m from the north façade so that it could not be read as part of the elevation.

Figure 9 represents some random solutions arbitrarily extracted from those generated by the GS. It can be seen that there is a wide variety of possible solutions even within apparently limiting constraints.

Figure 10 shows the best solution found by the GS on the left, and also the guess that had previously been made about what could be the best solution for the roof monitors. The difference between that guess and the actual solution 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.

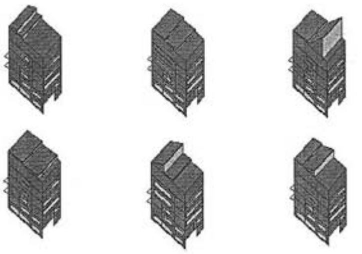


Figure 9.
Random roof tilt solutions generated by the GA

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 relate 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 zenithal 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 Siza 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 two-axis Stratasys fuse deposition modeling (FDM) 3D modeler was used, which deposits high resolution lines 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 those solutions from an aesthetics 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 tilts) 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 axis 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 under high pressure of water jets. This technique enables the unfolding or flattening of the individual pieces that are water jet cut, which can later be bent to achieve the original shape. 3D

Figure 10.
Best roof tilt solution generated by the GA (left) and initial guess of what might be the best solution (right)

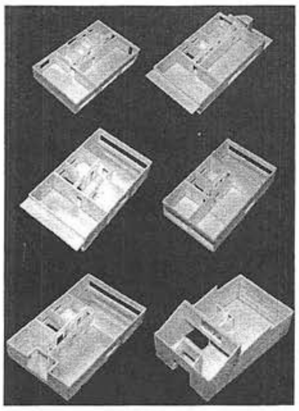


Figure 11.
FDM models of the six levels (top left is the first floor, bottom right is the sixth floor)

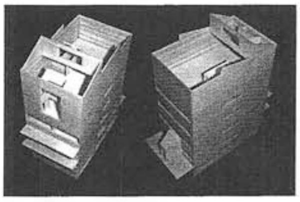


Figure 12.
FDM model of the complete building

Sterolithographic laser printing eliminates layers of a resin block, allowing fast execution of 3D models. Computer numerically contolled (CNC) machines, with multi-axis milling capabilities, can translate three-dimensional data into construction models, and constitute technological facilities that could also be used to create formwork for casting 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 genesis of the object as much as in the technical apparatus that permits its creation. By relating this new GS to RP techniques it is not only possible to generate and evaluate computationally generated forms, but also to evaluate spatially qualities of the several GA solutions, enabling thus a full integration of 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 coincidence between GS and Siza's solutions in some situations was of particular interest. On the other hand, the departures from the existing design proposed by the algorithm suggest 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 relations between the solutions for the loggia and the roof monitors, or between south and east facing windows in some of the studios, are a demonstration of that capability.

The ultimate objective in 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 definite or optimal answers, but as diagnosis of potential problems and as suggestions for further architectural explorations, building thus an innovative and promising interaction between architecture and computation.

The first attempts to do shape manipulation 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 relationships between design concepts and decision-making. CAD/CAM technologies can play a major role in the evaluation steps of the design process, especially when the latter makes use of GSs, where many solutions are developed at the design stage.

References

Caldas, L. and Norford, L. (2002), "Energy design optimization using a genetic algorithm", *Automation in Construction*, Vol. 11 No. 2, pp. 173-84.

Caldas, L. and Rocha, R. (2001), "A generative design system applied to Siza's School of Architecture at Oporto", *Proceedings of CAADRIA'01*, Sydney, Australia, 19-21 April, pp. 253-64.

Sullivan, R., Lee, E. and Selkowitz, S. (1992), "A method for optimizing solar control and daylighting performance in commercial office buildings", ASHRAE/DOE/BTECC Conference on the Thermal Performance of the Exterior Envelopes of Buildings V, 7-10 December, Clearwater Beach, FL.

Testa, P. (1999), "Evolutionary space in the architecture of Álvaro Siza", *A+U Architecture and Urbanism*, Vol. 355 No. 04, pp. 8-13.

Wetter, M. (2000), "Design optimization with GenOpt", *Building Energy Simulation User News*, Vol. 21, p. 200.