TetraScript: Development of an Integrated System Capable of Optimizing Light in a Circumscribed Space

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Abstract: The purpose of this research is to develop a process capable of optimizing the capture of light in a circumscribed space, using a responsive system of skylights. Research is focused on the design of irregular dome-like pavilion spaces circumscribed by curved surfaces, but the envisioned process might be applied to other functional, formal, and spatial typologies. The design of the pavilion starts with the generation of a surface, later tessellated into a matrix of skylights depending on the geographic location and sun orientation. In the constructed pavilion, the skylights react to the variation of daylight intensity during the day to satisfy specified internal lighting needs. Simultaneously, the integration of conception and fabrication using digital tools (CAD-CAM) facilitates the construction of a non-standard, parametric geometry, thereby diminishing the costs of production and allowing for personalization, while assuring global sustainability.

Keywords: Scripting; digital fabrication; automation; responsive system.

Introduction

In the actual stage of development, the building industry consumes a large quantity of matter, energy, and human resources. The result of this building model exhausts the available resources and has a strong impact on the environment. If we compare Nature’s strategies to use resources with those used by humankind, the latter are far less efficient. Nature optimizes the available resources by making use of general principles of material optimization and combining them with local processes of adaptation, thereby building with the minimal amount of matter and energy. This process is enhanced by natural selection, in an evolutionary process (Weinstock, 2004). The dominant strategy followed in the building industry requires a great amount of resources and it values economic aspects in a short term vision. In this context, the prevalent building technology gives insufficient relevance to local characteristics and the satisfaction of geographic constraints and individual demands for customization.

Technology is frequently seen as way of achieving economic power or economic assets, disregarding its potential to overcome local and environmental problems. This research intends to enquire into how new technologies can affect the building process, by making it more efficient, permitting customization, and allowing for the emergence of performative strategies taking local features into account.

Optimization models attempt to express in mathematical language, the aspiration to find the
best solution for a given problem. Previous approaches to use of optimization techniques in architecture have applied these two different stages of the design and building processes. The literature contains examples of research concerned with material optimization (e.g. Weinstock, 2004), environmental design optimization (e.g. Caldas, 2003), mass customized fabrication (e.g. Sass et al., 2005), and environmental building control (e.g. Cardoso et al., 2007). These examples used complex approaches that required the development of specific tools which is out of the reach of the common designer.

The developed research proposes a simplified process that combines aspects of these approaches to develop a feasible process for designing a pavilion that optimizes the capture of daylight, using existing parametric CAD tools. The proposed process includes three independent but linked stages: (1) the development of a design system for generating solutions adequate to different geographic locations using a programming language of high abstraction (scripting), (2) the materialization of such customized solutions using CAD/CAM techniques (fabrication), and (3) the use of an automatic system for controlling the skylights to guarantee the desired amount of light in the interior of the pavilion (automation).

The paper will focus on the first research stage, although the second and third stages will be briefly described.

In the first stage, a computer program was developed, in Visual Basic, to generate, optimize, and divide a pavilion surface into individual skylights that can open to control the amount of lighting in the enclosed space. Every component has the shape of a pyramid, with four triangular faces that rotate around their base axis to control the size of the opening and the amount of available light. Using the written code (script) different parametric variations of the skylights where tested. Different interfaces where experimented to take light input into account and guide the generation of design solutions. In the first attempts light inputs were external inputs. The final solution evolved to link local and global factors, as they become interdependent.

A practical application, of a dome-like pavilion, was developed to optimize light gains taking into account geographic location and maximizing the capture of light. This shape selection was done manually, although in the future an automated process could be implemented to respond to different constrains.

In the second stage physical reality, material properties, and scale were considered in an attempt to continue the optimization of the generated shape in response to structural, and fabrication constraints. Oriented strand board (OSB) was the chosen material for constructing both the surface and its underlying structure, which is assembled with metal connectors. This material is low-priced, lightweight, resistant, and suitable for digital fabrication, thereby making it possible the production of customized components. This research of the material aspects of the design will make use of previous experiences in wooden structures as described in “Crafting new artifacts: Expressing the changing condition of nature, culture and technology” (Henriques, 2007).

Peculiar geometric properties give relevance to the connection system, as an important factor, to assure structural integrity, construction and assemblage. A full-scale prototype here just briefly described will be addressed in more detail in a future paper.

In the third stage, a centralized intelligent system is being envisioned to control the system of apertures taking into account external climatic factors and internal lighting needs. By applying the algorithm created in the first stage one obtains values for the degree of openness of all the skylights, based on local and global lighting conditions. By combining the algorithmic information and local data values measured by sensors, a more compete environmental status could be available for the system to control the behavior of the skylights. This data can be transmitted to a central intelligence machine (a computer) and to a controller interface (a PLC, that
The point's information is stored in an array, and will constitute the geometric basis of further elements. Using a cycle (for-next) this data is called and used to create a diagrid, that is the base for each skylight. The original surface, is divided by the script in a set of quadrilaterals until it is completely tessellated (a subroutine was created for odd or even number of skylights and for the corner exceptions). From the center of the surface of every quadrilateral in this diagrid, a vector is created to an external point, the apex of the pyramid. When the apex is defined, the surfaces of the triangular pyramid are created. The goal of changing the light in the interior can be achieved by the rotation of every face of this pyramid, on the basis vertex, thereby defining the degree of openness of the skylights.

The automation of processes enabled the testing of a family of solutions, instead of a single solution. By attributing different values to the parameters, different candidate solutions were generated. The number of components, in the U or V direction, can be adjusted to the chosen surface, its size and scale, and to fabrication constrains. The vector that defines the apex can be vertical or normal to the quadrilateral base, and with a predefined or random distance.

Being able to generate and test different variations in real time without a script would take a considerable amount of time and repetitive work, and it would change with different surfaces. The proposed process enables one to overcome such drawbacks.

The skin morphology of some vegetables is, programmable logic controller) to manage the skylights by informing local actuators and respond to climatic variations. The system's implementation can be achieved using distinct strategies and technologies. Different possibilities were analyzed, looking for a practical application. In the current research stage, the implementation of this process of automation is being tested in one module. This experience can inform the behavior and the architecture of the system that can be improved and upgrade further on.

**Design generation**

**Main code development**

To define the skylights, a surface is required, as a geometric support to start with. The surface and the components can be created manually using standard modeling commands in Rhinoceros. The creation of complex surfaces is enabled by the program, and would not have been possible to achieve using other standard CAD programs (like AutoCad). Nevertheless, after the conception of the surface the creation of the components required a long time to be completed.

The repetitive procedure, done first manually, was described as a sequence of tasks in an algorithm. The automation code was written in the Rhino script editor, using visual basic (VBA).

The algorithm uses the given surface as a starting point, dividing it in the UV domain of the surface.
fruits as a response to different sun conditions con-
stituted a visual lexicon for the test of different pa-
rameters in different surfaces (Figure 2)

**External data input: Table, bitmap and form interfaces**
The process of creating skylights to control the 
amount of light in an interior space suggested dif-
ferent procedures and interfaces to be tested. Nor-
mally the manipulation of data using an interface as 
message box, slider (or other standard forms avail-
able in visual basic) is friendlier for the general user. 
The modification of values in the script line would 
require programming abilities and different skills.

The first interface, used data created in an excel 
table as input for the Visual Basic code. In this table 
with the same number of elements of the surface, 
values from 0 to 6 where used to control the aper-
ture of every skylight. This is an expedite process to 
change the values fast and see the results applied. 
A subroutine was developed to start with the given 
apertures of the table and gradually increment the 
values, resulting in the progressive closing/opening 
of the skylights.

Later on, a different input was tested using the 
color information from a chosen bitmap. A small 
program was written to transform images, and their 
pixel values, into numerical values, outputting them 
to an excel table (thanks for Augusto Sousa). Using 
the previous procedure the data was applied for the 
opening of the skylights. Using images or gradients 
was done with bitmaps created in other image pro-
grams (e.g. Photoshop, CorelDraw) of photos in a 
more visual approach.

Finally using Microsoft Visual Studio, a form with 
slide bars was created, enabling a friendlier interface 
for the user, to control apertures directly, but the ap-
lication was limited to the application of the same

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*Figure 2*  
Shape generation: morphology of existing plants/fruits; Skin tessellation and surface folds

*Figure 3*  
Shape generation (scripting): test and generation of different interfaces to control skylight design
aperture to every skylight (or at least a synchronized variation).

The interfaces tested enabled the user to feed the model with external values, manipulating them. Nevertheless, with these interfaces the data for the aperture is independent from the starting surface.

**Local data input**
An algorithm relating the light vector, defined by the user (by setting the starting and finishing point) and local values of curvature was conceived. The program compared the given direction of the light to the normal vector in every point analyzed. By evaluating the center point of every quadrilateral created based on the original surface, local value of the normal and light direction are compared, resulting in different rotation values of the triangles that control the light aperture in every skylight.

Using this system, and knowing the position of the sun in every hour (during the day, month or year) the aperture can be determined. Local value can emerge in every component, thereby optimizing lighting conditions. An environmental condition is thus introduced.

**Practical application and shape optimization**

**Surface selection**
In the previous stage different surfaces were tested and populated with skylights. In first approaches, double curvature surfaces where tested, because of their self-supporting capacities. After the introduction of the algorithm relating local/global light, it became more suitable to test dome-like closed surfaces.

For practical reasons, a mockup was thought for an available space of 2x3x3m (later expanded to 4x6x3m), located in Oporto (41.8ºN, 80.40ºW). Candidate surfaces like box, semi-sphere, semi-spheroid and other shapes were tested in this space (Figure 4). The spheroid surface chosen occupies the bigger volume for this space, and it has a bigger surface to receive light.

**Components number, disposition and orientation**
After the selection of a base surface, different disposition and number of skylights were tested. The frequency and scale of the components in the selected surface (and space) are important to set relative size introducing a constructive logic, later implemented.

Similar elements to the skylights are found in the morphology of existing plants and fruits, with skin covering tessellated with sharp elements and surface folds. Emerson Porras studied the influence skin folds and spines of the cactus Echinocactus Grusonii, as a cooling factor decreasing surface temperature by producing shadow (text in www.designemergente.org/emergence/estrategias-emergentes). The height of the apex parameter was tested. After these experimentations, it became clear that the apex
height can be a factor of local adaptation and a suitable parameter was thought for Oporto location.

The algorithm relating global light and local apertures was tested with different sun orientations. Having the major axis on N-S or W-E, it produced different results. The major axis W-E will result in more sun incidence during the day. The number of skylights in U or V directions also affected this phenomenon: if there are more skylights in U than in V they will be narrower in one direction and vice-versa. Different solutions were compared, relating the amount of surface receiving light, and the best solution was chosen.
Results

Programming tools, in this case with the use of written scripts were a helpful tool to diminish manual labor and enabled the testing of different solutions by changing some parameters, with fast visualization of results.

The process of selecting a shape (surface) to feed the script, for the implementation of the skylights is manual, but can be fully automated in the future. The implementation of a more detailed analysis, based on geographical and sun data can enhance the selection process.

Results discussion

First generation cad programs like Auto-Cad are based on Cartesian logic: the objects are defined in world space as discrete entities, without any relation to others objects created. With the advent of topological geometry, software opened new possibilities. As noted by Kolarevic (Kolarevic, Branko in Designing and Manufacturing Architecture in the Digital Age), the introduction of Nurbs (Non-uniform Rational B-Splines) enabled a new logic of continuity for curves and surfaces, defined with more precise mathematical definition. Changing local condition can affect other entities in an associative logic. Rhinoceros uses this second generation software, which facilitates the manipulation of continuous surfaces with standard commands. Nevertheless, to populate the surface with skylight, there was the need to introduce an algorithmic procedure, to learning the Visual Basic language, which revealed to be a tool that permitted to achieve more complex solutions and different objectives.

Software is evolving faster and it has a growing influence on all stages of the design process. In the described case, visual basic was the language used in the generation phase. In a near future, the use of object-oriented languages could become common place, or other languages might evolve. What is definitely changing, is the structure and the process of form selection from the design point-of-view. An algorithmic structure can favor performance-driven design using techniques such as shape grammars, shape annealing, scholastic methods, or genetic algorithms.

Conclusions

The research described in this paper is part of a larger research that aims to uncover the potential of the use of digital technologies in architecture, particularly for developing more sustainable buildings. Research used the design of a daylight responsive pavilion, called TetraScript, as a case study and the paper is focused on the generative process of the design of the pavilion. Nevertheless, the use of digital technologies was transversal to the design, fabrication and automation stages. So the argument is that technology in general, and scripting in particular, can enable customization and permit architecture to respond to geographic and individual requirements. The architect can regain the link with the technology of his time, thereby expanding his own abilities.

Responsive buildings can represent a shift and a
more ecologic approach to architecture, leading to a new modernism (or positivism) in a cybernetic world where nature and science can synthesize.

The project of the pavilion TetraScript, which was developed without direct funding, was a success in involving different experts, departments, universities, cities, and industries. However, to expand and continue this investigation, specific funding might be necessary as the cost of further access to technology increases. This suggests that the development of sustainable architecture using advanced technology might be jeopardized by financial limitations.

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