Botanics and Parametric Design Fusions for Performative Building Skins

An application in hot climates

Salma El Ahmar[1], Antonio Fioravanti[2]
[1,2]Sapienza University of Rome
[1,2]{salma.elahmar|antonio.fioravanti}@uniroma1.it

Biomimicry and computational design are two growing fields of research and practice in architecture for their potential in performative and sustainable design, among many other benefits. Cooling loads are posing serious energy problems in hot climatic cities as in Cairo and Alexandria. Attempting to solve these problems, this research turned to botanical inspirations for ideas in order to improve thermoregulation of the building skin. One of these ideas was chosen and implemented using computational software in the design of a parametric vertical shading screen for a typical office room in Cairo. The challenge was to minimize cooling loads as much as possible without compromising daylight requirements. An evolutionary solver was used to optimize results and environmental simulations were performed before and after the proposed screen to assess its performance and evaluate this biomimetic-computational approach to design.

Keywords: *Biomimicry, Building skin, Thermoregulation, Parametric design, Hot climates*

INTRODUCTION

The elevating problems of climate change throughout the world in addition to increasing use of non-renewable energy sources are creating a sense of urgency for fundamental changes needed in many industries, and the building sector is no exception. According to the United States Energy Information Administration (EIA), almost 40 per cent of total energy consumption in 2012 was by the residential and commercial sectors. These two sectors account for nearly all building-related energy consumption in the U.S. [1].

One of the key considerations in designing energy-efficient buildings is their enclosure. This element has the capability of improving the building's performance in natural ventilation, managing heat transfer, redirecting and filtering daylight and eventually decreasing energy consumption for cooling. This is a major problem in hot countries such as Egypt where residential and commercial sectors accounted for almost 48 per cent of total energy consumption in 2010 [2], and air conditioners account for approximately 20 per cent of energy consumption in buildings (Attia, et al., 2012).

The motivation arose to investigate new design ideas for building skins that could help solve such problems. Turning to nature was chosen for this investigation, since nature possesses a '3.8 billion-year' history of experience dealing with complex problems for survival. Much of the problems we face today have already been addressed and solved in effective, sustainable, and creative ways by natural organisms. Thermoregulation in hot climates is achieved by organisms using numerous strategies, each of which either minimizes heat gain or maximises heat loss. Plants in particular have many similarities with buildings, most importantly is that they are rooted and fixed in their location, and therefore were chosen as the starting point of this investigation.

On the other hand, digital modeling and simulation tools together with computational design and simulation processes are facilitating the realization of complex forms of many contemporary buildings. One of the opportunities to fully explore the potential benefits of biological principles for performative design, is by means of these technologies and tools.

AIM AND METHOD

This paper is a part of an ongoing doctorate research in which the aim is to couple biologically-inspired ideas with computation through a performative design perspective (El Ahmar, et al., 2013). . Such aim would be achieved by practically applying a biomimetic approach in designing a parametric skin for a building in Cairo to improve its performance by decreasing cooling loads while maintaining daylight needs. The performance of the proposed skin would be evaluated by comparing simulations of cooling loads, insolation on the façade and daylight before and after the new skin.

In this paper a focus has been made on botanical inspirations specifically regarding the problem of minimizing heat gained by incident solar radiation. A primary objective is to discover a number of plant strategies which are presented, analysed and simplified for further use. A preliminary parametric design of a skin for a typical office room in Cairo based on one of the analysed strategies is presented. A translation into mathematical terms was needed in developing the proposed preliminary parametric model, which was be simulated to discuss its environmental performance in terms of thermoregulation and its effect on daylighting.

The software used is Grasshopper plugin (v. 0.9.0075) for Rhino 3D modeller and DIVA plugin for environmental simulations. DIVA-for-Rhino is a highly optimized daylighting and energy modelling plug-in for the Rhinoceros - NURBS modeller. The plug-in was initially developed at the Graduate School of Design at Harvard University and is now distributed and developed by Solemma LLC [3]. Galapagos evolutionary solver is used for optimization.

There are generally two main approaches to biomimetic design; a Problem-Based and a Solution Based approach. The two approaches have been addressed in literature such as Zari (2007), Knippers (2009), Helms et al.(2009), and Biomimicry 3.8 [4]. This paper follows the first approach where the design problem addressed is thermoregulation of a building skin for hot climates. In order to effectively search for ideas in nature, the design problem must be as specific as possible. The exploration began asking the questions of: how do plants minimize heat gain and/or maximize heat loss? The intention is not just to mimic what an organism looks like, but rather how its form or behaviour serves its needs to survive.

STATE OF THE ART

Many strategies have evolved by organisms living in hot climates to prevent overheating. These strategies are both physical as well as behavioural. Examples include being light in colour to reflect heat, having long limbs to be farther from the ground, having more blood vessels near the surface of the skin in order to increase heat loss, staying active only at night and dawn, building ventilation tunnels as in termite mounds, taking refuge underground, in pools of water if available, and even going into a type of dormancy called estivation within the hottest months of the year (Mazzoleni and Price, 2013).

Biomimetic building skins could be found in both academia and, less commonly, in professional practice. They originate in contexts where creativity and sustainability are prioritised, and costs are relaxed to some extent (Loonen, et al., 2013). Some examples include research at Stuttgart University such as the HygroSkin Project (Menges & Reichert, 2012) in which surfaces inspired from Conifer cones could passively respond to humidity changes, the Flectofin Project (Knippers & Speck, 2012) where a hinge-less louver system (inspired from the Strelitzia reginae flower) was designed to move its fin by 90 degrees by inducing bending stresses or temperature change to it. Examples could also be found in research projects in the Architectural Association School of Architecture, the Austrian Institute of Technology, and in the MIT Media Lab among many others. Biomimetic skins in practice could be seen in some of the works of HOK, Michael Pawlyn, Grimshaw Architects, Atelier One, also among others.

HOW DO PLANTS REGULATE HEAT?

Trees and plants are flexible structures that are sensitive to climatic conditions and as a response, they have developed a number of techniques and features that aid in overcoming such situations. Only leaves, tree barks, and succulents were thoroughly studied and analysed to explore the strategies which they generally use to aid in thermoregulation (Table 1).

It is important to note that transferring ideas from nature to architecture was not found to be a clear and easy task to do. Since the aim was to regulate heat, the process of heat transfer is broken down to its main types which are radiation, conduction, convection and evaporation (Allen, 2005; Mazzoleni and Price, 2013). They serve as the common ground between the strategies of natural organisms and the corresponding architectural features. The main architectural features of a building skin which might affect each of these modes of heat transfer are listed as follows:

- Radiation: size, shape, location of openings, shading elements, skin overall morphology, reflectance, emittance of outer material.
- Conduction: thermal resistance, thermal capacity, material thickness, material arrangement.
- Convection: ventilation system, size, shape, location of openings, (de)humidification system.
- Evaporation: (de)humidification system, ventilation system, skin permeability, use of phase-change materials.

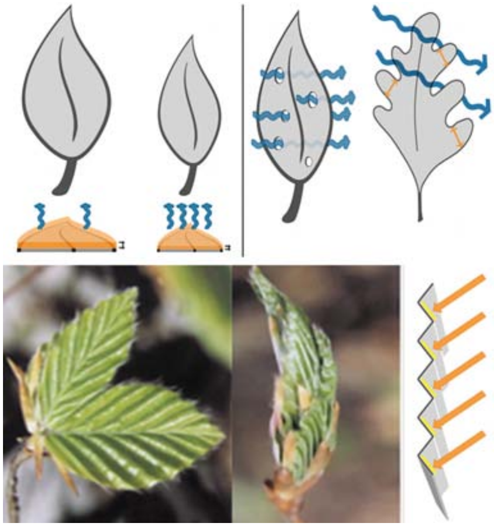

Figure 1
Smaller leaf size decreases the boundary layer (BL) resistance (top left), holes and lobes (top right) in leaves decrease the distance to the closest edge and decrease the BL resistance and improve free convection. Hornbeam leaf (bottom left) (Kobayashi, et al., 1998). Schematic cross-section (bottom right), indicating that the folds shade parts of the leaf from sunlight.

Leaves

Leaves are physical and biological entities that are extremely differentiated, either on the level of different species, or even within the same one. The huge variation of shapes and sizes of leaves have long been a topic of research, indicating that it is a part of an adaptive response to different climates, and different microclimates within the same tree or plant (Schuepp, 1993). These adaptations either minimise heat gain or maximise heat loss. It is worth noting that leaves depend on two types of convective heat loss; thermally-driven (free) convection in the form of upward flows, and wind-driven (forced) convection represented in lateral air movement (Vogel, 2009).

A number of strategies have been observed to aid leaves in avoiding overheating such as smaller size, the presence of lobes, dissections, holes, tearing, and folds among other strategies (Schuepp, 1993; Vogel, 2009; Givnish, 1988; Kobayashi et al., 1998; Ehleringer et al., 1976; Jones and Rotenberg, 2011). Some of these strategies tend to decrease the Boundary layer (BL) which is a thin zone on the surface of a leave where air does not move due to surface friction. For transpiration to take place, water vapour must pass this layer to reach the atmosphere. The bigger and wider the leaf, the thicker the boundary layer becomes and therefore resistance to transpiration increases (Schuepp, 1993).

Tree Barks

Leaves are not the only tree elements that contribute to cooling and thermal regulation, but also tree barks have an important role. Tree barks have always attracted people's attention due to their appearance, and despite their diversity that makes it seem difficult to find common thermal regulation strategies, they all serve the function of efficiently delivering water to leaves. And since leaves could sustain temperatures (usually) no more than 40 to 50 degrees Celsius, the water that reaches them must therefore be cool even in hot environments. Excessive heating could also affect the tensile water flow in the Xylem tissue below the bark (Henrion and Tributsch, 2009).

Unlike leaves, barks are not capable of cooling by evaporation. Therefore they have evolved other strategies to remain cool. They include having a round cross-section, rough textures, peeling surfaces, a thick insulating outer layer, and being optimised not for reflecting the visible spectrum of solar light (of wavelengths between 380 and 750 nm), but rather for the filtered (transmitted) and reflected light from surroundings (which is a part of infrared light of wavelengths of 700 to 2000 nm) (Henrion and Tributsch, 2009).

Figure 2
Different bark morphologies. Auracaria auracana; left, Pinus canariensis; center, and Aloe dichotoma; right (Henrion & Tributsch, 2009).

Succulents

Figure 3
Golden Barrel cactus (left) that has a relatively small surface area to volume ratio, spines, and folds that aid in thermal regulation. Cereus schottii (right) with smooth alternate curves for self-shading and light reflection.

Succulents are plants that have thick fleshy tissue that has adapted to the storage of water. Some of them such as cacti have no leaves (or very small leaves) and store water only in the stem, while others (e.g. agaves) store water in their leaves. They are native to environments with arid to semi-arid climates and have therefore evolved a number of features for thermal regulation [5].

Their strategies include closing stomata during the day and opening them at night when the temperature has decreased and relative humidity has increased to decrease water loss by transpiration. In this case the process of photosynthesis occurs at night as carbon dioxide is absorbed and combined with an acid in a process called Crassulacean Acid Metabolism (CAM) (Jones and Rotenberg, 2011).

The concept of self-shading is widely used among succulents. Varying from spines and protrusions, ribbed surfaces, grooves, or smooth alternating concave and convex surfaces such as in Senita

Table 1
Summary of some strategies of leaves/barks/succulents that aid in thermoregulation. Each strategy is described pointing out its main principle, which helps in finding the corresponding architectural feature to study.

Leaf Strategy	Description	Feature	Main principle	Arch. Feature
Small, narrow size	It decreases Boundary Layer (BL) resistance enhancing heat dissipation by convection	Size	Free convection	-Ventilation system
Lobes and dissections	They decrease the distance from any point on the leaf to the closest edge thus decreasing its temperature, + decreases the BL resistance	Shape	Free convection	-Perforations
Holes	Holes permit air to pass through the leaf+ decreases the BL resistance	Shape	Free convection	-Perforations
Folds	Folds result in parts of the leaf to be constantly shaded	Shape	Minimise radiation	-Skin Morphology
Avoid horizontals	Decreasing the angle of incident light reduces heat gain	Orientation	Minimise radiation	-Skin Morphology
Pubescence	Hairs increase reflection and decrease BL resistance	Surface Texture	Minimise radiation	-Cladding material
More or bigger stomata	Increase the leaves' ability to lose heat through transpiration	Molecular properties	Evaporation	-Ventilation system
Bark Strategy	**Description**	**Feature**	**Main principle**	**Arch. Feature**
Round cross-section	Decreases exposed surface area	Shape	Minimise incident radiation	-Skin Morphology
Thick outer layer	Provides an efficient insulating layer	Shape	Minimise conduction	-Insulation -Cladding material
Rough surface	Increases the area of shaded bark surface	Surface texture	Minimise incident radiation	-Cladding material
Peeling surface	Peels create air gaps in between serving as additional insulation	Surface texture	Minimise conduction	-Morphology -Cladding material
Reflection of non-visible light spectrum	Barks are optimised to the reflection of infrared light rather than visible light (which is about half of incident sunlight)	Molecular surface properties	Minimise incident radiation	-Cladding material
Succulent Strategy	**Description**	**Feature**	**Main principle**	**Arch. Feature**
CAM	Photosynthesis occurs at night. Stomata are closed in daytime and preserve water lost in evaporation	Metabolism	Minimise water loss by evaporation	-Ventilation system
S/V ratio	Smaller surface area to volume ratio minimises exposed surface area in relative to its volume decreasing heat transfer rate	Shape	Minimise conduction	-Overall building morphology
Ribs and folds	Increases the area of shaded surfaces	Shape	Minimise incident radiation	-Skin Morphology -Shading elements
Spines and hairs	Hairs increase reflection and in some cases decrease BL resistance	Texture	Minimise incident radiation	- Cladding material
Alternate curves	Increases the area of shaded surfaces	Shape	Minimise incident radiation	-Skin Morphology -Shading elements

(Cereus schottii). These seeming irregularities decrease the incident angle of light as well as reflect and scatter part of it (Hadley, 1972). Those which have hairy spines help also collect dew droplets and funnel them down the grooves to combine with other droplets forming bigger ones and decreasing their chances of being lost by evaporation (Ju, et al., 2012).

FROM NATURE TO ARCHITECTURE AND COMPUTATION

After exploring a number of plant strategies, the main principle (heat transfer method) of each was listed to find a corresponding analogy in architectural terms. This paper only addressed the strategies related to minimizing heat gain by minimizing incident solar radiation. There are many possible biomimetic ideas as seen in the previous section.

Among those, the authors had particular interest in the idea of folding that was seen in leaves as well as in cacti and was chosen to start investigating the design of the building skin. The reason behind this choice is that folding strategies have more than one benefit; they achieve self-shading of the building skin, they can orient faces towards or away from the sun depending on their position, and they could be rather easily translated into mathematical geometric relationships for computational modelling. The concept of folding is not new to architecture and is inseparable from Origami explorations. It has been explored numerously because of its potential as a creative form finding method, and also due to the resulting strength of the corrugated structures.

The investigation here however is interested in the benefits such forms can present in decreasing cooling loads of a space. There are various folding patterns that could achieve the intended. The pattern explored here is that of the Hornbeam (Figure 1) and Beach leaves, which also represents the basis of the Miura Ori pattern.

The design goal is to design a building skin that decreases heat gain and maximizes heat loss as much as possible without compromising minimum needs of daylight. According to LEED v.4: instead of the commonly used Daylight Factor, now they require spatial Daylight Autonomy (sDA) which is a standard requiring 50% of occupied hours during the year to be adequately day-lit (between 300-3000 lux) for at least 55% of occupied floor area (USGBC, 2013). Daylight Autonomy at a point in space is the fraction of the occupied times per year, when the required minimum illuminance level at the point can be maintained by daylight alone (Reinhart and Walkenhorst, 2001).

The design idea is to propose a folded perforated screen as a second façade layer to a typical office room in Cairo. The sides that face upwards towards the sun would be solid or have small openings, while the others facing downwards would have openings with varying sizes. The size of each opening will depend on the amount of the incident solar radiation on its face.

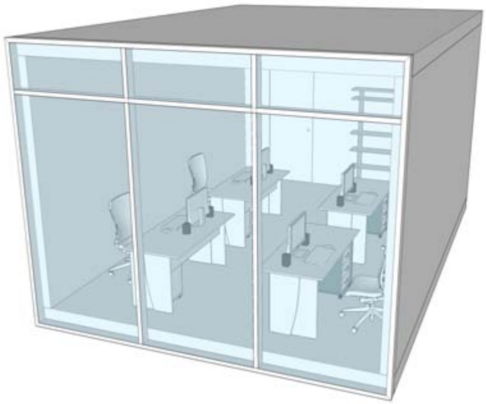

Figure 4
Typical furnished office room with double-glazed insulated curtain wall.

Model setup

A digital model of a typical office room is set up, with dimensions of 4*6 meters and 3 meters high, with a south-facing curtain wall façade made of double-pane insulated glazing (Figure 4). The room accommodates four people. Only one room (zone) is studied for now as this is a limitation of DIVA simulation plugin. The façade of the room comprises two layers; an inner one representing a typical office facade, and an outer layer representing the proposed folded screen.

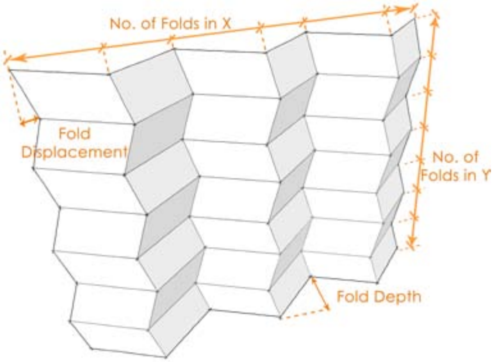

Figure 5
Conceptual sketch of the Miura Ori pattern, illustrating design parameters that will serve as genomes for the Galapagos evolutionary solver to minimize insolation on each face.

The first step was to define a surface that would be folded to act as the shading screen. This surface was divided in both the horizontal and vertical directions creating a grid of points. The even horizontal rows of this grid were selected and moved in the horizontal direction to create the fold displacement. Then the vertical columns of points were selected and moved in a direction perpendicular to that of the façade surface to create the fold depth. A surface is created from the new set of points, forming the folded façade based on the Miura Uri pattern. The design parameters (as shown in Figure 5) that we have considered are:

- Number of folds in the X axis
- Number of fold in the Y axis
- Fold displacement
- Fold depth

So far we still do not have any openings yet. To determine their size, we decided to calculate the insolation on each face, and then the opening size would be a function of that value. There are lot of possible combinations between the parameters stated above. Instead of manually trying every possible combination, these parameters were set as Genomes in Galapagos, and the fitness function was set to minimize the average value of insolation on all faces.

The search range (minimum and maximum value of each parameter) was set at the beginning. After solver the search range was adjusted accordingly. The opening of each face depended on the insolation value, the bigger the numerical value, the smaller the opening. After adjusting the search range, daylighting simulations we performed, this time new parameters are explored (the previous ones are now fixed and not subject to change):

- Thickness of the skin
- Smallest opening size
- Biggest opening size

The Galapagos solver is used again for these new parameters, with the fitness function set to minimize cooling loads while keeping a minimum illuminance value of 300 lux at four key nodes. The position of these nodes is the centre of four desktops placed the office room (Figure 4) with a height of 76 cm from the floor. Initially sDA simulations were intended to be used, however they take a lot of time, especially when used with Galapagos as it could keep on running for days using the available computers (Processor: Intel core i7, 3.5 GHz, RAM: 32 GB). Illuminance values were used instead just to give an indication of the best possible combinations of the new parameters.

In the end, one of the results (Figure 6) achieving the least cooling loads was chosen to run a single accurate sDA simulation (Figure 7) on a grid of nodes with 60 cm spacing in the whole room to be sure that at least 55% of the analysis nodes receive 300lux or more during half of the occupied hours. The sDA alone however would not tell us if parts of the space are over-lit, which is particularly important to know in cities that have relatively low cloud coverage and almost continuous sunshine throughout the year as in Cairo. So a check was also performed when certain points receive an illumination value above 3000 lux for more than 5% of the year. This check is important as glare and overheating could occur. Annual insolation on a vertical grid of points located just behind the glazing was also measured before and after the presence of the screen for comparisons (Figure 8).

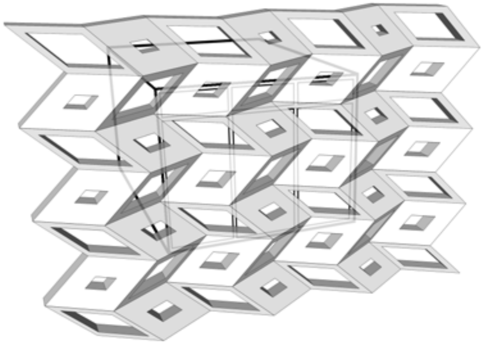

Figure 6
Final selected instance of the folded screen after optimization: 7 folds in X & Y, displacement= 0.87m, depth=0.7m, screen thickness= 0.34m, panel sizes= 1.3*1.2m.

Results

The concept of folding as seen in leaves and cacti continuously provides self-shading to the building skin partially protecting it from the sun and causing a big decrease in heat gained by radiation inside the office room. The flexibility of the parametric model with all its variables provided a wide variety of shapes and sizes of folds, and sizes of openings. With the help of the evolutionary solver, a balance was found among these variables that minimised heat gain while providing enough daylight for the occupants as well. The nature of this folded morphology enabled much of the light to enter in an indirect manner (through folds facing downwards).

The following values were calculated before and after the presence of the folded screen for comparison:

- Annual insolation
- Daylight Autonomy
- Over-lit areas
- Annual cooling loads

The same settings were always used such as materials, occupancy schedules, weather files, accuracy level, etc. The results seen in Table 2, show that traditional curtain-wall systems typically used in Cairo provide high sDA, however this is accompanied by high insolation and over-lit nodes. Here 60% of the space is over lit , usually causing a occupants to use blinds and therefore decreasing the daylight entering the space and eventually using electric lighting most of the day. After the folded screen is placed, a significant decrease in insolation and cooling loads is observed. The minimum daylight needs were achieved with a much less over-lit area (just 14% of the space). This indicates a better distribution of light throughout the room. The decreased over-lit area not only means less heat gained by radiation, but also an increased real estate value and efficiency of the office space since a bigger area could be comfortably used.

	Before Folded Skin	**After Folded Skin**
Annual insolation (average of all calculated points)	508.4 KWh/m2	115.5 KWh/m2
Daylight Autonomy (300lux, for 50% of occupied time)	100% of space	62.9% of space
Over-lit points (nodes above 3000lux)	60% of space	14% of space
Annual cooling loads	3970.2 KWh	2964.5 KWh

Table 2
Comparison of simulation results before and after the placement of the folded screen.

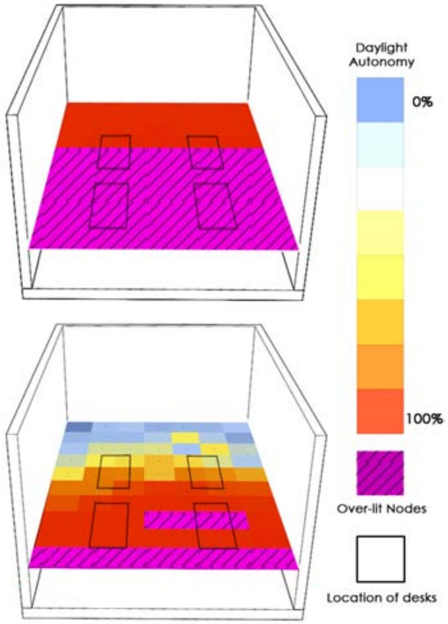

Figure 7
DIVA simulations of Daylight Autonomy and over-lit nodes before (top) and after (bottom) the folded screen. Positions of desks are outlined in black.

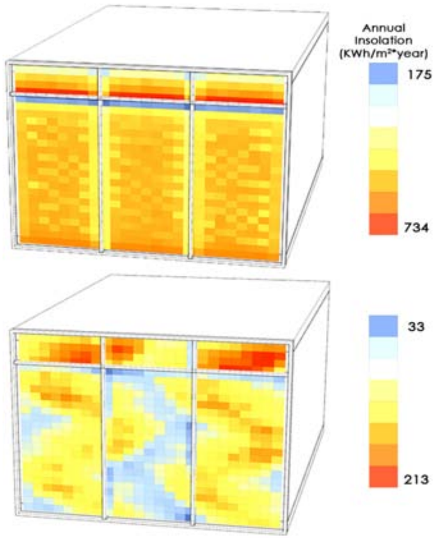

Figure 8
DIVA simulations of Solar Insolation analysis before (top) and after the screen (bottom).

CONCLUSION

This paper aimed at discovering and applying botanical inspirations for thermoregulation of building skins. In a biomimetic-computational design approach, a number of strategies are abstracted and analysed and one of which was chosen to design a preliminary parametric skin for an office building in a hot climatic area. The design challenge was to decrease cooling loads while maintaining at least the minimum daylight standards.

Exploring how nature solves problems that we are facing in design, gives us insights and guidance to sustainable solutions, and often leads us to think of unconventional yet efficient ideas. The paper presented a list of biomimetic ideas (Table 1) that could serve as guidelines for designers aiming to improve the thermal performance of building skins. It demonstrated with the help of computational design software and environmental simulations that such biomimetic ideas are worth exploring for the improvement they have shown in environmental performance. The evolutionary solver proved particularly useful in finding best results when conflicting aims are needed (decreasing cooling loads vs. increasing daylight).

One of the drawbacks regarding this design process is the time spent at the beginning where biological organisms are explored. The presence of a biologist in the design team would facilitate the process. Another issue was the long simulation times needed to obtain accurate results, in addition to limitations regarding the geometry complexity. When the number of folds exceeded a certain value, thermal simulations would not function posing a serious obstacle along the way.

The presented research will continue in the exploration of nature including a more comprehensive analysis and classification of all discovered ideas. Furthermore, future work will study not just the morphology of the skin, but also its materials, structure and behaviour as a whole.

REFERENCES

El Ahmar, S., Fioravanti, A. and Assem, M. 2013 'A Methodology for Computational Architectural Design Based on Biological Principles', *Proceedings of eCAADe 2013*, Delft, pp. 539-548

Allen, E. 2005, *How Buildings Work: The Natural Order of Architecture*, Oxford University Press, New York

Attia, S. and Gratia, A. 2012, 'Development of Benchmark Models for the Egyptian Residential Building Sector', *Applied Energy*, 94, pp. 279-284

US Green Building Council, USGBC 2013, *LEED Reference Guide for Building Design and Construction. 4th ed.*, USGBC, Washington

Ehleringer, J., Bjorkman, O. and Mooney, H. 1976, 'Leaf Pubescence: Effects on Absorptance and Photosynthesis on a Desert Shrub.', *Science*, 192(4237), pp. 376-377

Givnish, T.J. 1988, 'Adaptation to Sun and Shade: A Whole-plant Perspective', *Plant Physiology*, 15, pp. 63-92

Hadley, N.F. 1972, 'Society Desert Species and Adaptation: Plants and animals in arid environments show many striking similarities in their morphological and physiological adaptations', *American Scientist*, 60(3), pp. 338-347

Helms, M., Swaroop, S.V. and Goel, A.K. 2009, 'Biologically inspired design: process and products', *Design Studies*, 30(5), pp. 606-622

Henrion, W. and Tributsch, H. 2009, 'Optical solar energy adaptations and radiative temperature control of green leaves and tree barks', *Solar Energy Materials & Solar Cells*, 93(98–107), p. 98–107

Jones, H.G. and Rotenberg, E. 2011, 'Energy, Radiation and Temperature Regulation in Plants', in Hetherington, A.M. (eds) 2011, *Encyclopedia of Life Sciences (eLS)*, John Wiley & Sons, Ltd

Ju, J., Bai, H., Zheng, Y., Zhao, T., Fang, R. and Jiang, L. 2012, 'A multi-structural and multi-functional integrated fog collection system in cactus', *Nature Communications*, 3, p. 1247

Knippers, J. 2009 'Building and Construction as a Potential Field for the Application of Biomimetic Principles', *International Biona Symposium*, Stuttgart

Knippers, J. and Speck, T. 2012, 'Design and construction principles in nature and architecture', *Bioinspiration and Biomimetics*, 7(1), p. 015002

Kobayashi, H., Kresling, B. and Vincent, J. 1998, 'The geometry of unfolding tree leaves', *The Royal Society, Proceedings B*, 265, pp. 147-154

Loonen, R., Trčka, M., Cóstola, D. and Hensen, J. 2013, 'Climate adaptive building shells: State-of-the-art and future challenges', *Renewable and Sustainable Energy Reviews*, 25, p. 483–493

Mazzoleni, I. and Price, S. 2013, *Architecture Follows Nature: Biomimetic Principles For Innovative Design*, CRC Press, Florida

Menges, A. and Reichert, S. 2012, 'Material Capacity-Embodied Responsiveness', *Architectural Design*, 82(2), pp. 52-59.

Reinhart, C.F. and Walkenhorst, O. 2001, 'Dynamic RADIANCE-based Daylight Simulations for a full-scale Test Office with outer Venetian Blinds', *Energy & Buildings*, 33(7), pp. 683-697

Schuepp, P.H. 1993, 'Leaf Boundary Layers', *New Phytologist, Tansley Review*, 125(3), pp. 477-507.

Vogel, S. 2009, 'Leaves in the lowest and highest winds: temperature, force and shape', *New Phytologist, Transley Review*, 183, pp. 13-26.

Zari, M.P. 2007 'Biomimetic Approaches to Architectural Design for Increased Sustainability', *Sustainable Building Conference.*, Auckland

[1] http://www.eia.gov/tools/faqs/faq.cfm?id=86&t=1

[2] http://www.idsc.gov.eg/Upload/Documents/304/electricity.pdf

[3] http://diva4rhino.com/

[4] http://biomimicry.net/about/biomimicry/biomimicry-designlens/biomimicry-thinking/

[5] http://www.britannica.com/EBchecked/topic/571271/succulent