Biomimetic-Computational Design for Double Facades in Hot Climates

A Porous Folded Façade for Office Buildings

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Biomimetic design is an approach that is gaining momentum among architects and designers. Computational design and performance simulation software represent powerful tools that help in applying biomimetic ideas in architectural design and in understanding how such proposals would behave. This paper addresses the challenge of reducing cooling loads while trying to maintain daylight needs of office buildings in hot climatic regions. Specifically, it focuses on double skin facades whose application in hot climates is somewhat controversial. Ideas from nature serve as inspiration in designing a porous, folded double façade for an existing building, aiming at increasing heat lost by convection in the façade cavity as well as reducing heat gained by radiation. The cooling loads and daylight autonomy of an office room are compared before and after the proposed design to evaluate its performance.

Keywords: *Biomimicry, Parametric design, Double facades, Performance simulation*

INTRODUCTION

Cooling loads represent around 20% of building energy consumption in Egypt (Attia, et al., 2012) and is becoming one of major reasons of power shortages especially during the summer months. The building skin plays a critical role in determining the amount of heat gain in buildings and is therefore the focus of this study.

Most investigations about double facades were done in temperate climates, aiming at increasing buoyancy-driven not wind-driven natural ventilation and the difference between cavity and ambient temperatures could reach 20°C (Barbosa & Ip, 2014). In fact the bigger the temperature differences the better the buoyancy effect and natural ventilation. However, having such a great increase in cavity temperature will not be favourable in hot climates where ambient temperatures are relatively higher. Therefore their application in hot climatic areas is controversial and still needs investigation.

An overview of current techniques for naturally ventilating double skin façades was needed to understand how airflow would generally behave and what the factors that affect it are. An interesting review paper by Barbosa and Ip (2014) identifies the main parameters influencing the thermal and energy performance of such facades. They provide a set of guidelines for each design parameter which were important to take into consideration. Some of these guidelines are suitable for hot climatic areas. For example preferred cavity depth should be between 0.7 and 1.2 m, the multi-storey and shaft type structures have a stronger stack effect increasing ventilation rates, importance of using double glazing, bigger air openings that aid in extracting warm air out of the cavity, and that decrease in cavity temperature does not vary in a linear way with opening sizes.

Hamza (2008) compared a single façade and a double façade with three possible glazing options; transparent, tinted and reflective. The single façade acts as a benchmark base case representing a typical office building in Cairo. Results indicate that careful material choice is critical to the thermal performance of the double façade, as reflective glazing provides the most reduction in cooling loads. The façade had air openings at the top and bottom. The use of shading devices was not addressed.

Another study was conducted by Radhi et al. (2013) in the United Arab Emirates. They compared an east-facing double façade system that had openings at top, bottom and at each floor, with a classic single façade system. The upper cavity opening induced the stack effect causing upper floor to experience more heat gain, but at the same time it was responsible for removing the heat out of the cavity. They estimated a 17% reduction in cooling energy on a typical summer day due to the performance of the double façade.

An interesting study done in central Italy by Baldinelli (2009) explored the use of an unconventional double façade made of L-shaped movable glass and aluminium shading panels that could rotate using hydraulic jacks to take one of two positions; an open state for summer and a close state for winter. Cooling loads were 10.3 KWh/m2 for the proposed design, 151 KWh/m2 for a fully glazed single façade and 77 KWh/m2 for 50% glazed single façade, which shows that double facades could be used in warm climates if certain design aspects were taken into consideration.

Studies regarding double facades usually consider the outer façade layer a as a flat vertical surface with not much geometrical complexity, and the daylight performance resulting from the presence of these double facades has been rarely addressed in correlation with their thermal performance. In the search for new ideas for buildings skins in hot climates, the researchers turn to biomimetic design to explore possible solutions.

AIM AND METHODOLOGY

In a previous paper (El Ahmar and Fioravanti, 2014) we defined a number of possible biomimetic inspirations and categorised them based on the heat transfer methods; radiation, conduction, convection and phase change. One inspiration related to decreasing gain through radiation was chosen (which was folding strategies) as a starting point and was applied in the design of a shading screen for a typical office room.

This paper builds upon previous work and widens the scope to study the reduction of heat gain by convection as well as radiation. The biological inspiration addressed in this case is termite mound behaviour in natural ventilation. The main design challenge is decreasing heat gained by radiation and increasing heat lost by convection in the cavity of a proposed double facade, with the aim of decreasing cooling loads and improving thermal comfort. Another important aim is to study visual comfort simultaneously, so that decreasing cooling loads would not be at the expense of reducing daylight performance.

The design is developed using computational parametric software, together with real-time environmental analyses which provide instant feedback as the design progresses. These tools proved to be particularly useful especially when there are conflicting design needs at hand. The performance of the proposed skin is evaluated by comparing the simulated cooling loads and daylight performance of an office room in an existing building in Cairo before and after the skin is placed. Figure 1 describes the overall applied biomimetic-computational design methodology applied in this research.

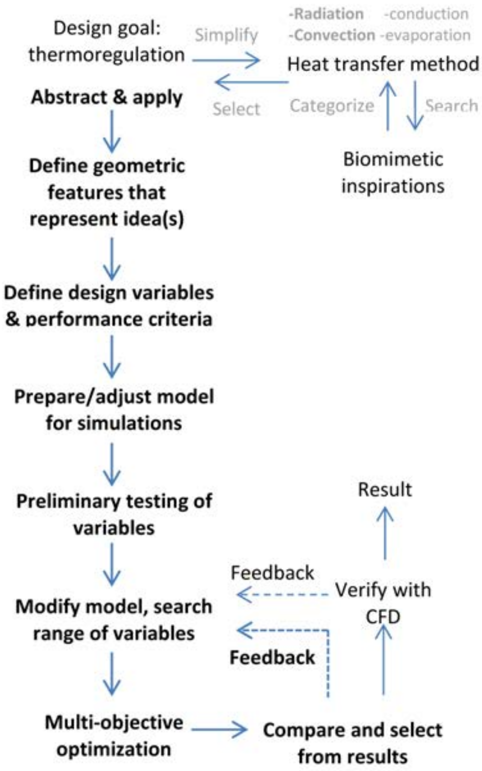

Figure 1
General research/design methodology. Scope of this paper is in bold.

BIOLOGICAL INSPIRATION

Termite mounds are one of the famous biomimetic examples known for natural ventilation strategies. *Macrotermes michaelseni* termite mounds are found in sub-Saharan Africa, they are closed cone-shaped mounds that could extend several meters in height, with a porous skin and an underground nest with a diameter of 1.5 to 2 meters (Turner, 2001). Turner and Soar (2008) highlight some misconceptions often associated with these ventilation mechanisms and offer a more accurate explanation of how the ventilation system actually works.

They explain that airflow in termite mounds is more complex than the two previously assumed airflow models; the thermosiphon model in closed mounds and the induced flow model in open mounds. The famous Eastgate building although succussful, is based upon these models that were found not be entirely accurate. Rather, the system is closer to a 'tidal' ventilation model in which air flow depends on temporal variations of the wind. Air in the the middle of the chimney, is under the effect of natural/free convection (buoyancy) pushing upwards, and forced convection pushing either up or down depending on the wind. In the end, air is in constant movement up and down in rough synchrony with wind conditions outside the mound. Wind is usually the dominant force.

It is beyond the scope of this paper to fully explain how the ventilation system works, however one of its important features is addressed here serving as the main inspiration for the architectural proposal. The porous mound surface plays an important role as air enters through it to a network of surface conduits that extend all around the mound. So regardless of wind direction, air could enter from one side of the mound and reach the other through the surface conduits. Air movement in this network is always due to wind. Then it passes through a reticulum of tunnels till it reaches the chimney causing the air to move either up or down depending on the resultant force as explained. The porous surface and the surface conduits act as a buffering layer protecting the interior of the mound from turbulent winds and enable the use of wind regardless of its direction

Analogy in architecture

As mentioned earlier, ventilation in termite mounds is a complex process. Therefore just a couple of important features serve as the main inspiration here. These features are simplified and abstracted to be able to apply them in an architectural context. Figure 2 explains the addressed features of the mound ventilation system and the corresponding architectural analogy.

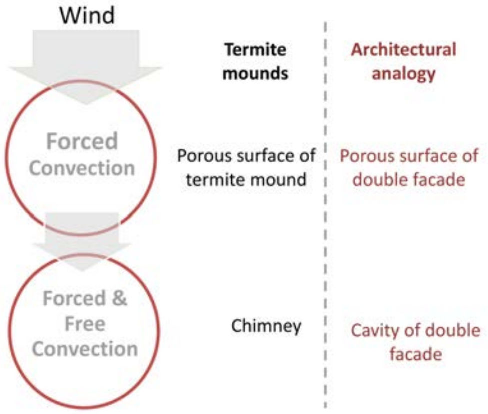

Figure 2
Inspiration from termite mound ventilation system and the corresponding analogy in an architectural context for designing a double façade.

Design objectives of the analogy

- To design a double façade with a porous surface that mimics an aspect of the ventilation behaviour in termite mounds
- Air flow in the cavity would be in constant movement and is a result of both wind and buoyancy forces either reinforcing or opposing each other, thus attempting to increase convective heat loss
- To design a folded surface that reduces heat gained by solar radiation due to self-shading
- Maintain visual comfort in the office space at least as it was before the folded façade, if not improved

Other buildings inspired by termite mound ventilation such as the Eastgate building in Harare, Zimbabwe, and the Davis Alpine House at Kew Gardens, usually apply the analogy on a whole building scale, by designing a central atrium within the building along with other features (Pawlyn, 2011). However in this research the scope is focused only façade design for an existing building and therefore the biomimetic inspiration is applied only to the façade to see its contribution alone in decreasing cooling loads.

Regarding the desired self-shading effect, many folding patterns can achieve this requirement. Aesthetic aspects are also important when deciding which pattern to choose. For this design proposal the triangular pinwheel pattern is chosen (Figure 3), it is seen as aesthetically pleasing and also all folded surfaces would be triangular and therefore flat, making it relatively easy to construct as opposed to double-curved surfaces.

COMPUTATION AND ANALYSIS

This section describes how the biomimetic concept was translated to a double-skin façade system. Preliminary sketches were transformed into a digital parametric model. Software used include Grasshopper visual programming language for Rhino 3D modeller, Octopus plugin which performs multi-objective optimization of design requirements using evolutionary algorithms, ArchSim Plugin which performs simulations in EnergyPlus v.8.2, and finally DIVA for daylight simulations.

Digital model of existing room

Only one office room from an existing building is assessed in this optimization process, representing a typical mid-floor space in the South Eastern façade with the dimensions of 5 m in width, 8 m deep, and 4.1 m high. This orientation was chosen as a start as it is one of the most challenging for thermoregulation of this building. The construction materials assigned are the same as those in the existing building; most importantly the façade has non-operable double-glazed tinted curtain wall panels (with light transmittance of 37%) and aluminium cladding. The technical specification of these materials have been requested and obtained by interviews and correspondence with the building owner/architect. The simulated annual cooling loads of this room are $139KWhm^{-2}$. This is in close accordance with actual readings of the building which indicated that average annual consumption is $113\ KWhm^{-2}$.

The Daylight Autonomy (300 lux, for half of occupied time) is achieved for 51% of the room area, however 37.5% of this area is over-lit, receiving more than 3000 lux in more than half of the occupied time. Daylight Factor minimum (which is a value of 2) was achieved in 36% of the room area. This fact is only important for later comparison of optimization results, as Daylight Factor calculations are much faster so they are used in the optimization process as an indication. Daylight Autonomy will be calculated only for the selected result for accurate comparison with the existing room.

Digital model of double façade

The triangular pinwheel is an iterative pattern that takes an input triangle and divides it in a certain way, then applies the same division logic again to the resulting triangles and so on. To have a folded surface made from this pattern, a certain point in input triangle is moved perpendicularly to its surface (Figure 3). The moved distance of this point controls the fold depth of each iteration. When applied to the double façade, the first iteration was extracted to act as the main structural elements that would bear the load of the façade. They also serve another function as they contain a network of small 2x2 cm perforations. This network extends throughout the façade to create the intended *porous* effect. Figure 4 demonstrates the composition of the proposed double façade.

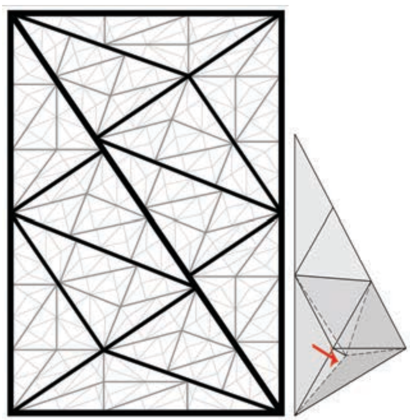

Figure 3
Left: Hierarchy of 3 iterations of the triangular pattern. Right: adding a third dimension to the pattern to create a folding effect. Each iteration could have a different fold depth that could be positive (outwards) or negative (inwards).

The main input in the grasshopper script is a 'base' vertical rectangular surface placed in front of the office room, exceeding the width of the room from both sides by 2 m. It starts at the first floor level till 1 m above the third (and last) floor. The folding logic is applied to this base surface. The double façade also has bigger openings at the very top at the height above the existing building to promote either wind catching and/or getting rid of hot air rising up.

Performance criteria. According to the required design goals, a number of performance criteria were chosen to represent the behaviour of the proposed idea. They include cavity operative temperature, cavity air flow measured in air changes per hour (ach) and Daylight Factor (DF) in the office space. They represent the 'fitness' in the evolutionary algorithmic solver Octopus which attempts to optimize design variables to reach the solution that achieves the best balance or trade-off between these criteria.

EnergyPlus simulations of the double façade take place on just one day that represents a typical hot summer day in Cairo (2nd of July) in which average ambient temperature is 32°C, average site wind speed is 4.9 m/s with a North West direction meaning that the façade at hand is in the leeward side of the building. This was due to the large computation time needed to run annual energy simulations for this relatively complex model with a huge number of small air openings. When a solution is selected, cooling loads for the month of July will be compared to those of the existing room.

Design variables. A number of design variables control the double façade morphology and therefore its behaviour. Table 1 describes each variable, the criteria that it influences and its search range in the evolutionary solver.

Preliminary testing of variables. The variables are numerous and simultaneously affect performance criteria. At the beginning all variables were given a default fixed value (mentioned in Table 1), and then each one is tested individually to see its effect on performance criteria and assign a suitable search range accordingly. Default values have the fol-

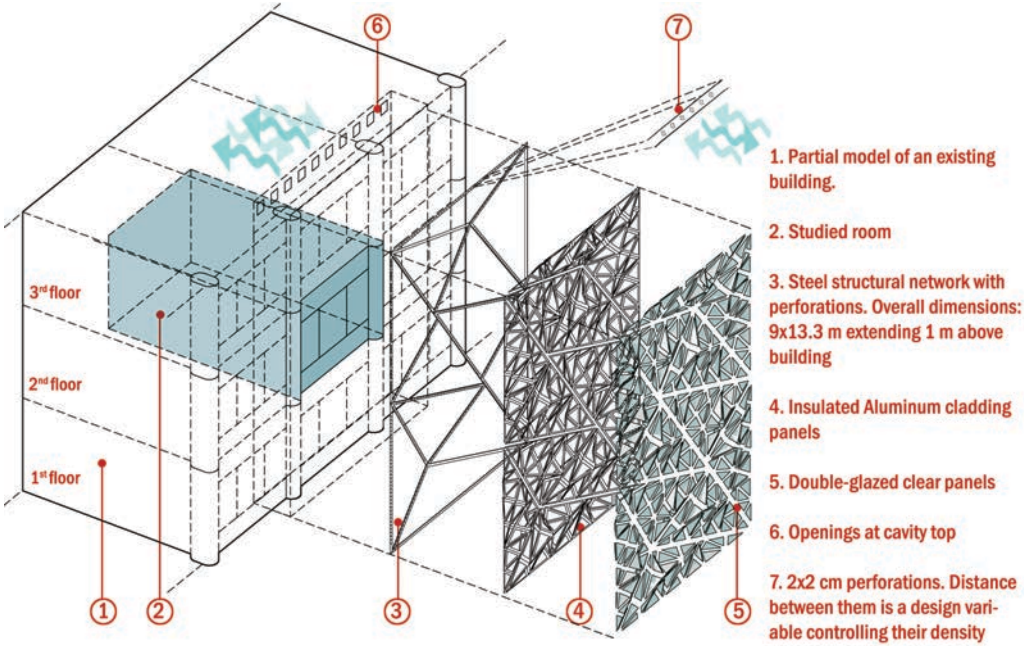

Figure 4
Diagram illustrating digital model of the studied room and the proposed folded porous façade.

Table 1
Design variables, their description and affected performance criteria. The search range of each variable is set after preliminary testing of a wider range for each variable alone to understand its influence.

	Affected performance criteria			Variable description
	Cavity temp.	Cavity airflow	DF	
1st iteration fold depth	X	X	X	Distance measured from the cavity depth value (either added or subtracted). Zero means no folding is done. Search range: -0.5 to 0.8 m. Default=0.
2nd iteration fold depth	X	X	X	Distance measured perpendicularly from each new folded face. Zero means no folding is done. Search range: -0.5 to 0.6 m. Default=0.
3rd iteration fold depth	X	X	X	Distance measured perpendicularly from each new folded face. They are smaller in size than the 2nd iteration therefore the allowed range is smaller. Zero means no folding is done. Search range: 0.2 to 0.5m. Default=0.
Cavity Depth	X	X	X	Distance between the inner surface and outer base surface of the double facade. Search range: 0.8 to 1.5 m. Default=0.8.
Glazing scale factor	X	X	X	A scale factor of each folded triangular face to create glazed openings. The size of opening is inversely proportional to the amount of insolation falling on its face. This scale factor controls the maximum possible opening size. Search range: 0.8 to 0.97. Default=0.7 (was before changing search range).
Distance between perforations	X	X	-	Area of openings is fixed 2x2=4 cm^2. Spacing controls their density. Search range: 0.15 to 0.25m. Default= not to be assigned.
Cavity top opening scale factor	X	X	-	A scale factor of rectangular openings at the top of the cavity. Openings face prevailing winds (NW). Search range: 0.6 to 0.9. Default= not to be assigned.

ings are assigned in default state), DF=17% of the room area.

The effect of some of them is clear. For example increasing glazing area increases cavity temperature (up to 35.6°C) and daylight value (up to 30% of space) as expected with slight increase in airflow. Air openings increase air changes per hour (up to 106 ach) as they increase, and decrease temperature (to 34.0°C).

As fold depths increase inwards (negative value) they slightly decrease temperature as insolation on each face decreases, and also daylight decreases, but airflow increases. For the folds of the second and third iteration, temperature slightly decrease even if they are folded outwards (positive value) due to the shading they create. Cavity depth had different effects on each criterion. As it increases, it slightly decreases temperature, clearly decreases airflow, and increases daylight as it approached 1.5 m then after that value daylight decreases. For fold and cavity depths specifically, their effect changes a lot with different default values of other variables, and with different combinations of each other.

An important observation is that an increase in airflow does not necessarily mean a decrease in temperature. This was true only to certain limit of air changes per hour (around 60 ach), after that limit the increase in airflow had no effect in decreasing temperature. This was important to understand; as it implies that airflow should not be assigned as an objective in the evolutionary solver because it would just try to increase it as much as possible. It would do that not understanding that it shouldn't try to increase it after this limit especially if this increase is at the expense of another objective being optimized in the same time. Therefore, optimizing the air-openings will take place in a separate process aiming to optimize temperature only without daylight as well, since daylight isn't affected by them.

Optimizing temperature and daylight

The search range for each variable has been modified based on these preliminary results, to avoid wasting time in trying solutions that will not produce good results. The assigned objectives are minimizing cavity temperature and maximizing daylight, and the variables are the first five of those listed in Table 1.

Best results (shown in Figure 5) for cavity temperature were obtained in many cases, but usually when first and second fold depths were at opposite extremes, and the third fold depth was always at maximum positive (folded outwards). Values near zero (complete flatness) for all three folds depths were always avoided. There was no clear preferred range for cavity depth. Best results for daylight did not show a clear preferred variable range as well. It was noticed that only the first fold depth tended to have a positive value (folded outwards) rather than a negative one. Many different combinations produced the same results.

A solution achieving a trade-off between cavity temperature and room daylight was selected (Figure 6) in which cavity temperature decreased to 34.7°C, and DF=23% of space. The DF is much better than the default case but still less than the performance of the existing room.

Optimizing temperature and airflow

The selected solution went through a final single-optimization process in which the variables assigned were the distance between porous openings and cavity top opening scale factor to see the effect of the porous surface and consequently convective heat loss on the cavity temperature and airflow. The fitness is set to minimize cavity temperature.

Results show that the presence of this network of perforations in addition to openings at the top had a big effect in increasing the airflow rate to an average of 60 ach and decreasing the cavity temperature to an average of 33.7°C after an average of 34.7°C without them. The difference between cavity and ambient temperatures is within the range of 1.7°C which implies that overheating is prevented at least in the specified typical day in which simulations were calculated. This shows the importance of increasing heat loss by convection in the thermoregulation of the double façade. Airflow is due to both natural and

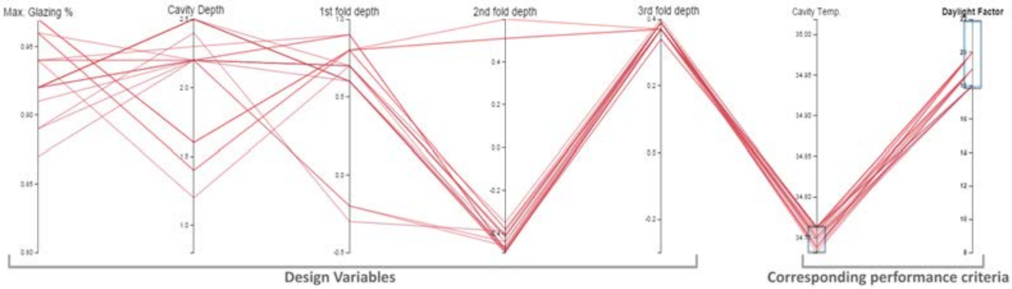

Figure 5
Visualising design variables that produced a trade-off between temperature and daylight. Image produced by 'Pollination' web-based application [1].

forced convection (wind), but forced convection is dominating. All solutions produced very similar results with a temperature range of 33.7°C. This is probably due to the narrowed search range that was assigned based on the results of the preliminary testing in the beginning. The chosen solution had openings at the top with total area of 7.2 m^2, and total area of perforations=1.48 m^2 (each is 2x2 cm^2, 0.19 m apart) and the cavity volume=237.6 m^3.

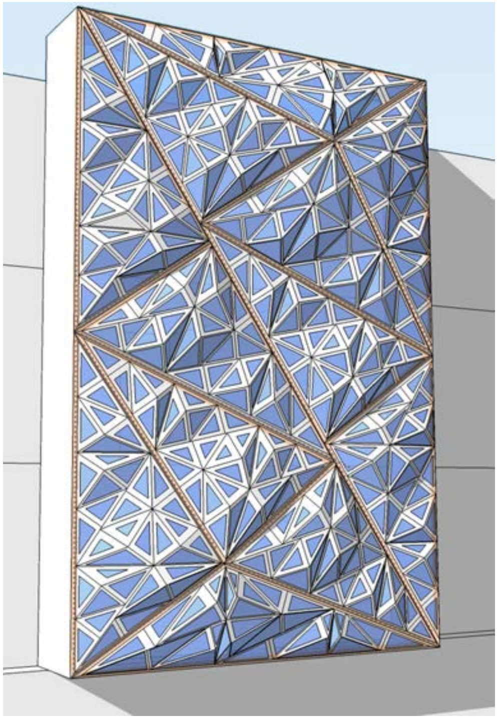

Figure 6
Selected solution; max. scale factor for glazing=0.99 (values inversely proportional to insolation on each face), cavity depth= 1.8m, 1st fold depth=0.5m, 2nd=0.24m, 3rd= 0.15m , scale factor of upper air openings= 0.9, distance between the small perforations= 0.19m.

Figure 7
Chart illustrating the performance of the cavity (its temperature and air changes per hour) with changing ambient conditions throughout the month of July. Wind direction is usually NW except for the 1st day and last week of the month when it is S/SE.

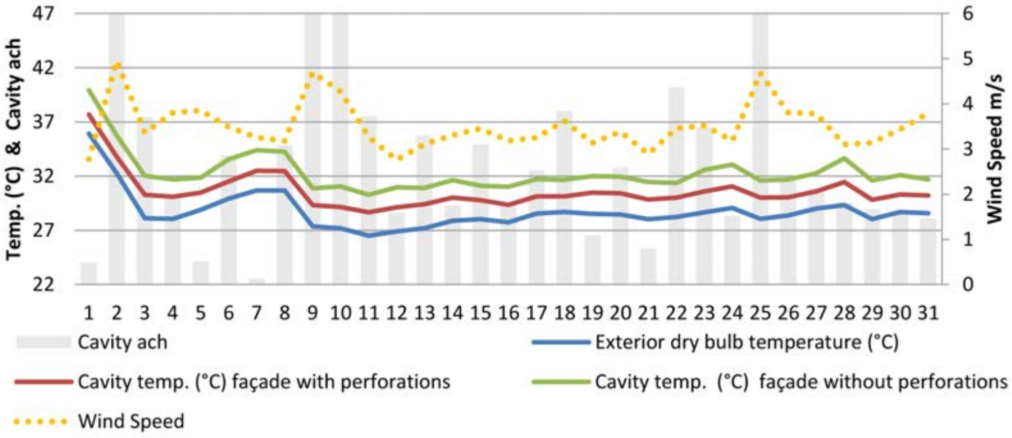

Figure 8
Daily cooling loads in July of the office room before and after placing the double facade

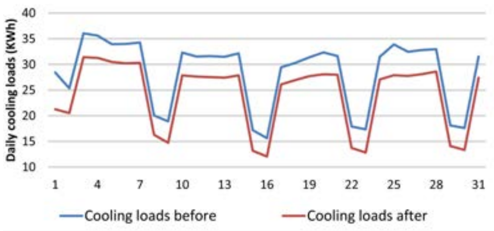

Table 2
Comparison of daylight and cooling loads of the office room before and after the placement of double façade.

EVALUATING SELECTED SOLUTION

Simulations have been repeated for the whole month of July. Figure 7 shows that cavity temperature is always around 1.7 to 2.0°C above ambient temperature even with changing wind speed and direction. This is quite important so that the proposed design would not be always dependent on a specific wind direction, increasing its efficiency. Cavity airflow throughout the month closely follows wind speed and had a minimum of 24 ach when wind speed was 2.7 m/s.

Table 2 summarizes the performance of the room before and after the double façade. The presence of this façade had a positive effect on cooling loads as they decreased by **15%**. However, it had a negative result on Daylight Autonomy which decreased to 45.2% of the space. This means that further modifications need to be done to improve daylight, such as using light shelves and more importantly using a glass type with higher visual transmittance than the one already used in the existing room, and then cooling loads should be re-calculated for evaluation and design modification. Figure 8 shows a comparison of the daily cooling loads of the room with and without the double façade.

	Before double facade	After double façade
Cooling loads for July (KWh)	879.75	747.7
Daylight Autonomy (300lux for 50% of occupied time)	51%	45.2%
Over-lit area of room (nodes receiving more than 3000lux)	37.5%	19.2%

Software limitations

It is important to point out the limitation of EnergyPlus in modelling double facades, as the Airflow Network model it uses assumes that each thermal zone has a uniform temperature distribution, and it does not take into consideration the cavity airflow pattern (EnergyPlus, 2014). Several studies (Zhang, et al., 2013; Sabooni, et al., 2012; Kim & Park, 2011) attempted to test the appropriateness of the Airflow Network model for simulating double facades, and concluded with the recommendation of coupling Energyplus with a Computational Fluid Dynamics (CFD) tool to complement each other's limitations.

CONCLUSION

The study demonstrates the potential of coupling biomimetic design and computational tools in designing a double façade for hot climates. It aimed at reducing heat gain by radiation by using a folded surface for self-shading, and increasing heat loss by convection by using small perforations inspired by the porosity of termite mound surface. Computational software played an important role in the development and analysis of the proposed design and understanding its performance to make modifications in early design stages when decisions are most important. All design variables affected performance criteria in different ways, the evolutionary optimization process proved useful in finding a trade-off between different conflicting objectives.

The proposed design was capable of reducing cooling loads, however its performance regarding daylight still needs improvement. It gives a positive indication that double facades can be used in hot climates if well shaded and ventilated. This paper is a part of an on-going research in which the following step is to repeat the same experiment in other façade orientations. This would be followed by CFD simulations of the double façade to get more accurate results regarding cavity temperature and airflow. This is important in order to know whether the results of EnergyPlus could be relied on to give an indication of the performance of complex double façades in early design phases in which the use of CFD tools is not practical.

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[1] http://mostapharoudsari.github.io/Honeybee/Pollination