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Multi-functional biomimetic adaptive façades: A case study

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Adaptive façades can be described as being able to express changes in form and function, and these changes are associated with desired aspects of building performance. Perhaps the best place to search for innovations in adaptive façades is in nature, where every organism has evolved multiple adaptations to survive in stressful environments. These strategies can be classified as dynamic or static depending on how they are induced by environmental stimuli. Translating strategies that control multiple parameters in biological organisms to the design of multi-functional biomimetic adaptive façades shows great potential. Given this, the research here explores dynamic and static mechanisms in nature to develop the design of a multi-functional biomimetic adaptive facade to improve thermal comfort in naturally ventilated buildings. A specific case study is designed from the principles of the morphological and physiological adaptations found in the barrel cactus (*Echinocactus grusonii*). These include: the form of the cortex; the morphology of areoles and spines; and plant responses to stressful conditions through opening and closing stomata. These adaptations are translated into a design of a multi-functional biomimetic adaptive façade. An environmental analysis for the case study is conducted with a defined performance target to improve thermal comfort in naturally ventilated school buildings. Simulations demonstrate there is a 51.5% improvement in 'ASHRAE55-2010 90% Acceptability Limits', and 67.5% in '80% Acceptability Limits' when incorporating the multi-functional biomimetic façade, as compared to traditional construction. The study demonstrates the performance potential of design generation from mechanisms in nature in the development of multi-functional adaptable facades.

Keywords: Biomimetic adaptive facades, case study, multi-functional, architecture, design

1. Introduction

One of the primary aims of environmental design is to deliver comfort. Thermal comfort is related to building performance and determines the well-being and productivity of occupants in different environments (Health and Safety Executive 1999). Moreover, discomfort may bring health issues due to low standards such as sick building syndrome (Environmental Protection Agency 2009). Thermal comfort can be improved through the successful design of building envelope and systems (Holmes and Hecker, 2007).

The façade is the barrier between the inside and outside of a building. Similar to the skin of animals or epidermal tissue of stems, the building façade withstands fluctuating climatic conditions. A successful façade design is expected to meet several functional requirements and regulate multiple environmental factors. In nature, there is an extensive array of organisms specialised in different functions. The translation of biological solutions into adaptive façades would benefit from billion years of evolution. Given this, the research here aims to develop an approach for designing multi-functional biomimetic adaptive facades. The first paper in this series (*Multi-functional biomimetic adaptive façades: Developing a framework* is also written as part of FAÇADE 2018 Final Conference of COST TU1403 "Adaptive Façades Network"), describes the development of a design framework that others can follow to design multi-functional biomimetic adaptive façades. This paper expands this, by demonstrating the implementation of the framework through a case study school building. The resultant multi-functional biomimetic adaptive façade is simulated to demonstrate its performance improving thermal comfort.

2. Multi-functionality in nature and architecture

Organisms have in-built adaptations with various functions in order to survive. The most efficient way to procure as many survival strategies as possible lies at the intersection of hierarchy and multi-functionality. Hierarchy in nature is having independent functional features in a multi-level structure from nano-to-macro scales. Each level in biological structures is comprised of similar elements but generates different parts (Knippers & Speck 2012). For instance, in plants, the stem structure is in the macro level of the hierarchy, followed by tissue, cell, cell wall and the biochemical composition of the cell wall which serves as the smallest scale (Speck and Rowe 2006). Multi-functionality in nature is the integration of more than one function into a single system where a unified structure is capable of controlling a variety of functions (Knippers & Speck 2012). Almost every organism has diversified functions at multiple levels of a single component in the hierarchy to withstand stresses, mostly caused by the thermal environment. In nature, efficiency in material and matter are vital for advancement; organisms evolved their adaptations as hierarchical and multi-functional structures as structure, function and form being often carried in the same substance with quite fluid boundaries. It is difficult to determine the function of an element in isolation of its other uses.

While this is the case in nature, on the contrary, in architecture, buildings are composed of individual components with separate functions often performing single tasks. Current studies concentrate on mono-functional elements assembled into a single system that is subsequently multi-functional. For instance, components of a window are designed separately fulfilling different requirements, such as daylighting and external view controlled by glass` properties, while glaring and solar gains controlled using shadings. The façade needs to manage multiple aspects to meet the functional requirements of a building and protect the indoors from environmental factors such as wind, precipitation, humidity, outdoor temperature and solar radiation (Aelenei et al. 2016). Façade systems aim at meeting a wide range of various functional requirements that are often contradictory. For example, achieving optimum illuminance with minimum glare and having high thermal storage with lightweight, permeable structures (Gosztonyi et al. 2010).

The concept of adaptive façades is an emerging area integrating various functions into the building envelope with a focus on adaptability. The definition of adaptability in façades is the ability to meet various functional requirements to improve building performance to changing climatic circumstances. On the other hand, the successful design of an adaptive façade is substantially associated with multi-functionality. Multi-functionality in façades refer to façade systems having more than one functional requirement controlled independently. Therefore, the development of multi-functionality in façades can benefit from the integration of lessons learnt from biological structures.

3. Implementation of a framework for the development of multi-functional biomimetic adaptive façades

A new framework for the development of multi-functional adaptive façades is proposed to promote the translation of multi-functionality in nature into architecture. The framework consists three main steps: (1) the definition of boundary conditions and functional requirements, (2) selection and mapping of corresponding multi-functional biological adaptations, and (3) design generation for multi-functional biomimetic adaptive façades (Fig 1). The boundary conditions determine the required functions through a base-case model with a selected climate and building typology. The biological model is selected through a map provided as a growing database that is comprised of the investigation and classification of numerous multi-functional mechanisms in nature with their specific features such as their biological organisation levels, stimulus, adaptation types and levels. Design generation for multi-functional biomimetic adaptive façades is achieved through a series of translation of the biological adaptations. The biological organisation levels help transferring different functions in a hierarchical multi-level structure of an adaptive façade. The first two steps of the framework serve as the inputs for design. Boundary conditions give the technical design input and biological models give the biological design input. These steps define the technical problem as functional requirements to be solved by natural adaptations. The third and last step, the design generation, gives the strategy, therefore the output of the framework.

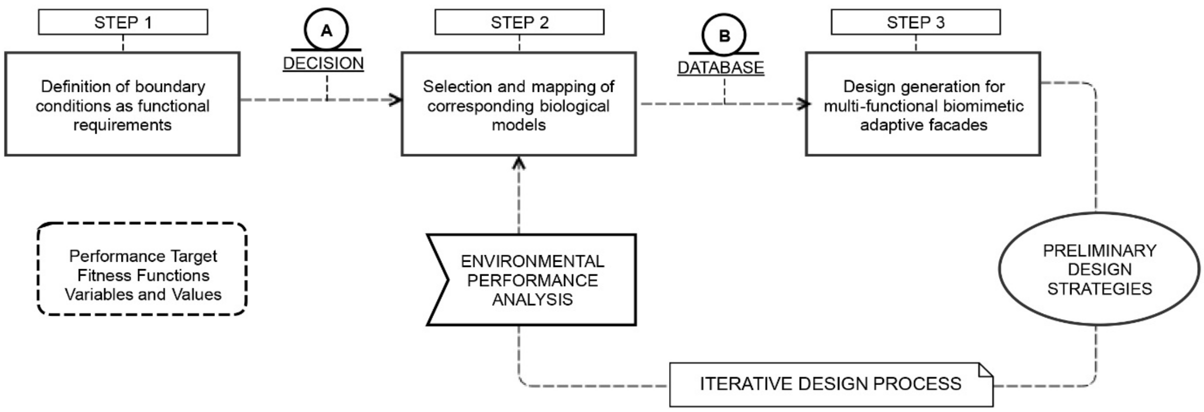

Fig. 1 A new framework for designing multi-functional biomimetic adaptive façades

In addition to the three main steps, the framework proposes a quantitative analysis of the developed façade design to analyse its environmental performance and determine the most promising design strategy. It is suggested that through a series of design generations of façades, the most promising option will be selected in terms of its performance through simulations. The target of the performance analysis and fitness functions are determined according to the boundary conditions identified. In this case study, the target is improving thermal comfort standards by controlling solar gains and ventilation. The fitness functions for the comfort analysis are ventilation rate, temperature, visible light transmittance and solar heat gain. The variables set for the building performance simulation are opening ratio and schedule, shading geometry and schedule; and materiality for thermal resistance and conductivity of the glazing. The case study acts as an example of implementing the framework demonstrates a design option and its performance as an outcome.

4. Definition of boundary conditions and functional requirements

4.1. Boundary Conditions

The boundary conditions are identified to determine the functional requirements to improve thermal comfort. This comprises the selection of a climate, location, building typology, architectural design of a specific building, local building regulations and the ventilation type. This paper focuses on Western Sydney, Australia. With the positive impact of being a coastal city, Sydney has mild winters and warm summers due to the presence of sea breeze (Glasow, 2013). In contrary to the situation on the coastline, inland areas especially the western part of the city suffer from hot temperatures in dense precincts (Santamouris et al. 2018). In this case, naturally ventilated buildings can be highly affected by the extreme climatic conditions resulting in greater occupant discomfort. A high-performing dynamic system regulating multiple environmental factors demonstrates a higher chance of improving comfort compared to a conventional approach (Fiorito & Santamouris 2017). Therefore the focus of this research is implementing dynamic façade systems in naturally ventilated buildings.

To determine the reference scenario of what happens in Sydney, a digital reference building from the United States Department of Energy (US DoE) was selected to serve as a base-case model. The typology was selected as an educational building. The reference building was located in Atlanta, USA, as Atlanta shows climatic similarity to Western Sydney. It is anticipated that the geometry of the reference building is suitable for a similar climate. Only one thermal zone, a corner classroom in the reference building, is modelled to simplify the simulation and modeling processes. The classroom was originally located in the South-West corner of a primary school. The corner classroom is rotated by 180° due to Sydney and Atlanta being in different hemispheres. Therefore, the corner classroom is now located in the North-East corner. The ventilation type is switched to natural ventilation from mechanical ventilation with 50% operable windows and external louvers to provide shading. Glazing type and its thermal properties, aperture ratio, shading`s slat data and dimensions and ventilation rate are compliant with National Construction Code (NCC) of Australian Building Codes Board (ABCB 2018).

4.2. Performance Analysis

The specifics of the reference building`s architectural and technical properties are listed in Table 1. The information provided in this table are not changed with the implementation of the new façade design. The values are taken from the original base-case digital building model from US DoE, followed by a compliance process for NCC of ABCB. Some changes are made to comply with the local building standards in Australia and to convert the ventilation type from mechanical to natural. The building simulation is conducted targeting thermal comfort analysis using Adaptive Comfort Model measures of ASHRAE 55-2010 Standards as simulation output. To demonstrate the climatic situation in Western Sydney, the weather file for Sydney Airport is used. Sydney Airport serves as a benchmark for the Western Sydney climate throughout a typical year similar to Bankstown and Sydney Olympic Park, which are located further in the west (Santamouris et al. 2017).

Table 1: Corner classroom zone data summary.

Parameter	Value
Floor area	97 m²
Volume	388 m³
Floor-to-ceiling height	4.00 m
Lighting load	15.06 watts/m²
Internal equipment load	15 watts/m²
Occupants density	0.4 people/m ²
Construction of external walls	Steel frame structured walls
External walls R-value	1.469 m²K/W
External walls U-value	0.681 W/m²K
Air change rate for natural ventilation	7.5 ac/h
Ventilation operation schedule	Always on when occupied
Infiltration rate	0.00302 ac/h

The openings data for the base-case building comprising of glazing, aperture and shading is provided in Table 2. A double glazed low emittance clear glass is replaced with the original digital reference model due to the previous glazing`s obsolete typology which was a single glazing with a poor performance. The double-glazed openings reflect the case of a high-performing scenario suitable for a comparison with an adaptive façade design. High solar reflecting and low transmitting louvers are also placed on the exterior of the façade and switched to always on throughout the year. The thermal properties of the shading system are kept the same for the new façade design to be able to compare the results for changes made in the typology and geometry of the biomimetic façade.

Table 2: Base-case glazing and shading properties summary.

Glazing	Parameter	Shading	Parameter
Type	LoE double glazed with 3 mm clear glass and 13 mm air gap	Type	High reflectance low transmittance louvers
Solar heat gain coefficient (SHGC)	0.598	Orientation	Horizontal external
Visible light transmittance (VLT)	0.769	Slat angle	45 – 90° (maximum)
U-value	1.798 W/m²K	Slat width	50 mm
Window-to-wall ratio (WWR)	35% glazed	Slat thickness	0.2 mm
Aperture	90% of the glazing	Slat conductivity	0.900 W/mK
Aperture location	Top	Shading schedule	Always on
		Solar reflectance	0.800
		Solar transmittance	0.100

The results for the performance analysis show that the total energy consumption of the building is 123.13 kWh/m² (Table 3). A significant amount of the energy use is due to lighting and equipment needs with 50.87 kWh/m² and 58.43 kWh/m² respectively. In contrast, heating is the least energy consuming element with a value of 2.77 kWh/m². The analysis is run to determine thermal comfort therefore the mechanical ventilation is out of operation. The analysis for the adaptive comfort model presents the number of discomfort hours annually in a typical year in two different categories for the acceptable range of indoor temperatures to the outdoor conditions. The results show that 1112.50 hours in total fall in the ASHRAE 55 90% acceptability limits and 685.50 hours in the 80% acceptability limits.

Table 3: Results of energy demand and discomfort hours for the base-case model.

Energy Demand		Number of Discomfort Hours	
Internal Gains	Energy Usage	ASHRAE 55 90% Acceptability Limits	ASHRAE 55 80% Acceptability Limits
Heating	2.77 kWh/m²		
Lighting	50.87 kWh/m²		
Internal equipment	58.43 kWh/m²		
Total	123.13 kWh/m²	1112.50 hours	685.50 hours

5. Selection and investigation of corresponding biological model

5.1. Selection

Simulation results show that solar gains and ventilation are major concerns affecting the performance. Therefore the functional requirements are maintaining and losing light and heat and gaining and exchanging air with the purpose of decreasing operative temperatures and increasing ventilation for cooling. The environmental factors and their controls assist in investigating the corresponding biological models mapped in a database. The database is further explained and explored in detail in '*Multi-functional biomimetic adaptive façades: Developing a framework*' also as part of FAÇADE 2018 Final Conference of COST TU 1403 "Adaptive Façades Network"). As a result of a selection from the database, some organisms were identified such as the barrel cactus *(Echinocactus grusonii)*, sensitive plant *(Mimosa pudica)* and big pine cone *(Pinus coulteri)*. For the purposes of this research, the barrel cactus was chosen as the biological model to pursue.

5.2. Investigation

The selected organism is investigated in the database to comprehend its multi-functional, adaptive and performative features. The database offers an extensive mapping and classification of organisms with various functions present at different biological levels regulating multiple environmental factors. Fig 2 shows the classification of the barrel cactus and its three primary mechanisms to regulate environmental factors; the expanding dynamic mechanism of the cortex; the self-shading static mechanism of areoles and spines; and the dynamic microscopic stomatal openings on the epidermal layer of the stem (Fig 3).

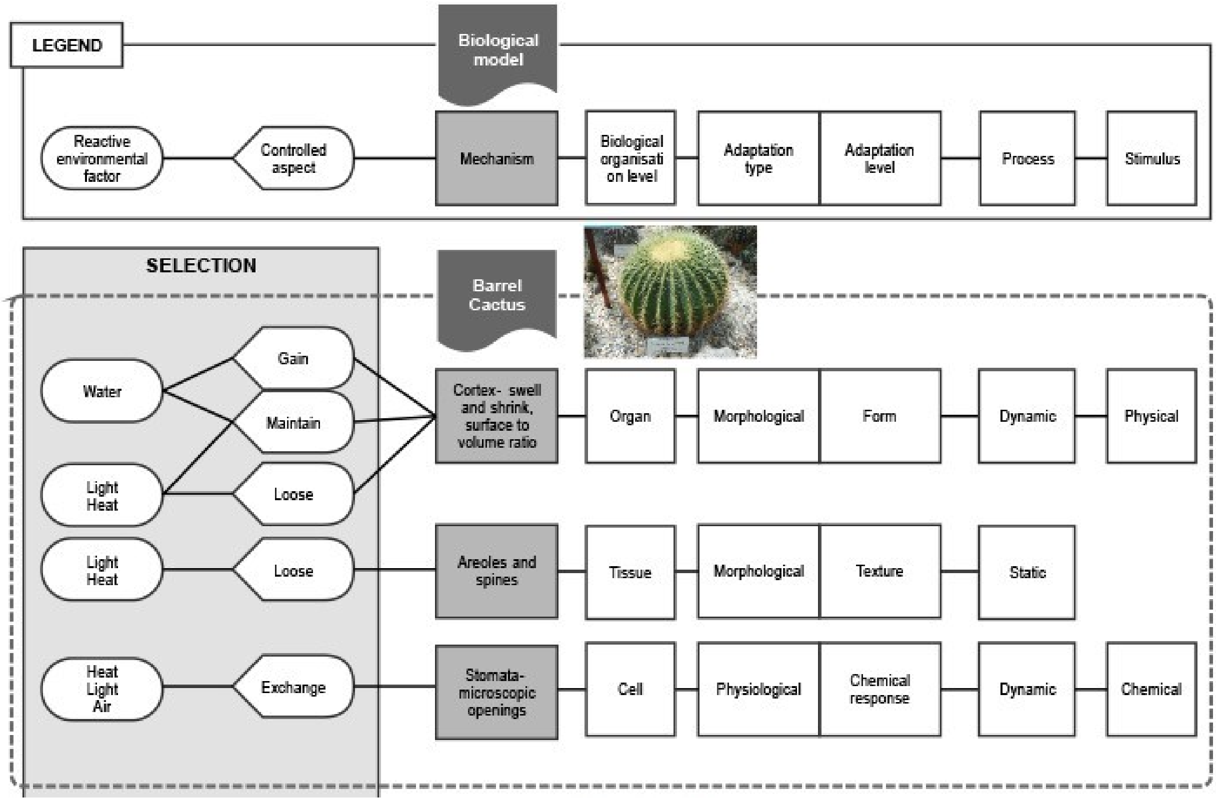

Fig. 2 Mapping biological mechanisms of the barrel cactus *(Echinocactus grusonii)*

a) b) c)

Fig. 3 The barrel cactus *(Echinocactus grusonii)* a) swollen, b) shrinking; and c) areoles and spines (Source: New York Botanical Garden)

The cortex is the stem of the cactus that is covered with a unique ribbed morphology. This structure of the ribs give the plant the ability to swell and shrink in response to changing internal water content and outside temperature. The barrel cactus is capable of expanding its surface area up to 54% helping losing heat by having a high surface-to-volume ratio (Nobel 1977). Ribs decrease the average plant surface temperature for both winter and summer days about 1-2°C. With the help of its areoles and spines, the barrel cactus creates shaded areas increasing this cooling effect. Areoles are unique structures to cacti situated on the epidermal layer of stems where spines grow. In fact, the difference between the hourly surface temperature of the stem with spines compared to without spines is 16°C in summer and 6°C in winter (Nobel and Gibson, 1986). The ribs, spines and areoles together decrease the average hourly surface temperature by 5°C for a summer day and 0.2°C for a winter day (Nobel, 1988; Nobel and Gibson, 1986). The stoma is a reversible, nastic structure operating as a valve on cactus` stem to balance the intake of carbon dioxide with water loss (Lee, 2010; Hopkins, 1995). The barrel cactus, like vascular plants, uses the stomatal openings to cool its stem surface and collect air by generating negative pressure through evaporation (Bar-Cohen, 2005; Stahlberg and Taya, 2006). There are between 15 to 70 stomata per/mm^2 in a cactus (Park et al., 2016). This number is much less than in other plants since cacti need to conserve water in their typically hot and arid habitat.

6. Design generation for multi-functional biomimetic adaptive façade

The two dynamic mechanisms of the barrel cactus which are ribs-structured expanding cortex and stomatal openings are transferred into a façade component to form a pattern replacing the whole façade of the base-case building. The stomatal openings are transferred into a dynamic opening system and the cortex morphology is transferred into an expanding shading system. The façade component is duplicated along x and y-axes to replace a whole façade. The shape of the component is a hexagon with a maximal radius and side length equal to 500 mm. Therefore, the height of a whole component measures 1 meter and four components will be covering the length of the whole façade. The two functional requirements of the façade are controlled individually through the difference in axes of displacement as movement in y-axis for ventilation and x-axis for shading.

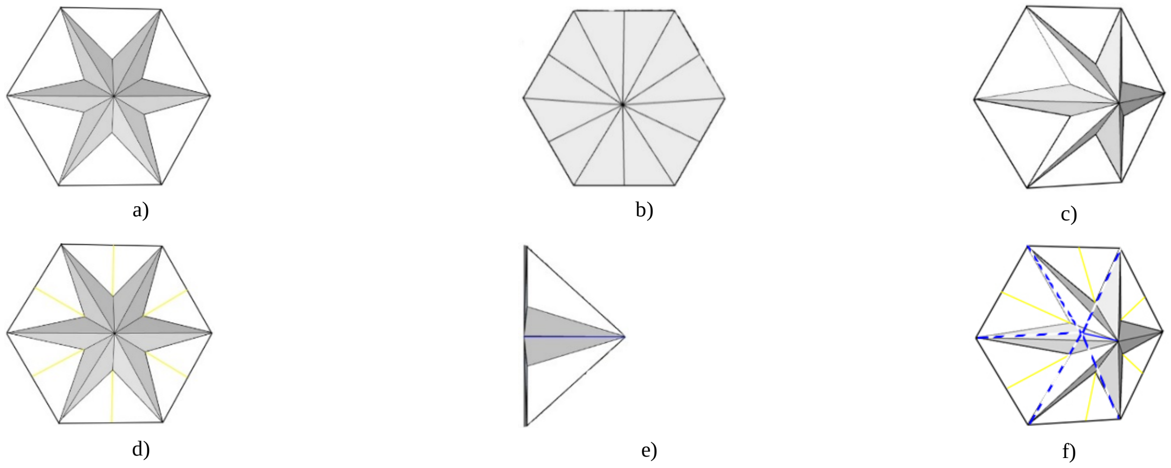

Fig. 4 a) Fully open/ventilating, b) fully closed/shading, c) intermediate/shading ventilating states, d) displacement in y-axis, e) displacement in x-axis, and f) displacement in both x and y-axes of the façade component

The thermal and material properties of the glazing are kept the same as the base-case model to determine the improvement by implementing the biomimetic adaptive façade as a new morphology (Table 4). The aim of the analysis is to focus on the different geometry and typology of the implemented façade. The whole façade is replaced with the biomimetic adaptive façade with a window-to-wall ratio (WWR) of 90%. The shading is modelled as a horizontal shading module mimicking the geometry with a dynamic movement following the occupancy schedule. When solar gains are higher than 120 W/m² the shading mechanism is activated. The mechanism allows maximum shading and ventilation at noon with an angle of 90° gradually reaching closure in the morning and the evening (Fig 5). The width of the slats are calculated as 500 mm and the thickness is 0.2 mm. The fully open configuration is measured as a 90% maximum opening. The expanding mechanism for is equal to the radius, side length and slat width of the component.

Table 4: Façade design modeling summary.

Glazing	Parameter	Shading	Parameter
Type	LoE double glazed with 3 mm clear glass and 13 mm air gap	Type	Expanding internal and external shading
Solar heat gain coefficient (SHGC)	0.598	Orientation	Horizontal
Visible light transmittance (VLT)	0.769	Slat angle	45 – 90° (maximum)
U-value	1.798 W/m²K	Slat width	500 mm
Window-to-wall ratio (WWR)	90% glazed	Slat thickness	0.2 mm
Aperture	90% of the glazing	Slat conductivity	0.900 W/mK
Aperture location	Top	Shading setpoint	On when solar gains are higher than 120 W/m²
		Shading control	Following occupancy schedule
		Solar reflectance	0.800
		Solar transmittance	0.100

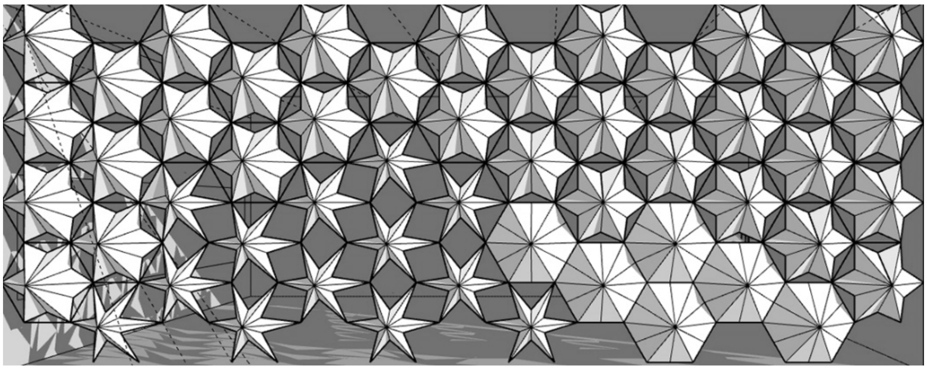

Fig. 5 Shading study of the whole façade design

7. Environmental performance analysis

An environmental performance analysis for an entire typical year in Sydney is conducted and the results show that there is a substantial improvement in comfort levels with the implementation of the biomimetic adaptive façade design (Table 5). The ventilation type and operation of the building are kept same as the base-case model as naturally ventilated with the same air change rate of 7.5 ac/h. The total number of discomfort hours are reduced according to the adaptive thermal comfort model by ASHRAE 55-2010 (Fig 6). The discomfort hours for Acceptability Limits 90% are reduced from 1112.50 to 540.50 (51.5%) and for Acceptability Limits 80% are reduced from 865.50 to 282.00 hours (67.5%). On the other hand, the total energy use is quite similar with an increase of 3.4% while the heating demand is more than doubled. It increased by 60.8% reaching 7.05 kWh/m² from the initial case of 2.77 kWh/m². This comparison shows that the summer discomfort hours are reduced substantially while winter discomfort hours are increased slightly with a need for additional heating.

Table 5: Results of energy demand and discomfort hours for the façade design.

Energy Demand	Value	Difference	ASHRAE 55-2010	Number of discomfort hours	Difference
Heating	7.05 kWh/m²	60.8% increased	90% Acceptability Limits	540.50 hours	51.5% reduced
Total energy usage	127.41 kWh/m²	3.4% increased	80% Acceptability Limits	282.00 hours	67.5% reduced

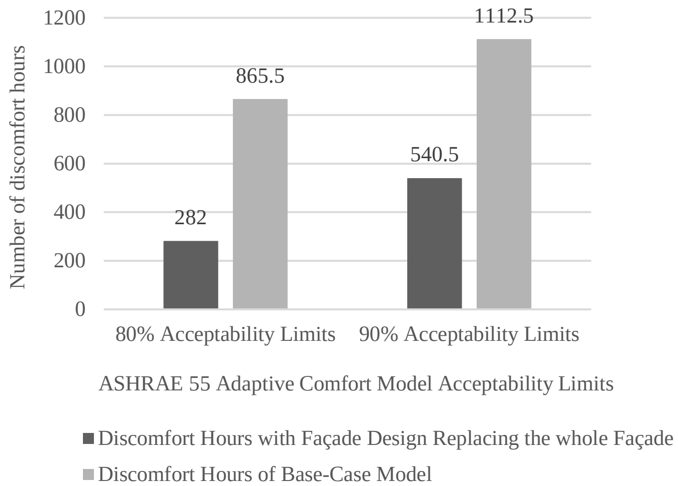

Fig. 6 Number of discomfort hours comparison between the base-case model and the façade design

8. Conclusion

This research demonstrates the implementation of a proposed framework discussed in the paper `*Multi-functional biomimetic adaptive facades Developing a framework*`. A double-side oriented corner classroom in a naturally ventilated primary school in Western Sydney is the reference scenario due to its high energy use and low comfort. An environmental analysis is conducted to calculate the number of hours not meeting Adaptive Thermal Comfort model for ASHRAE55-2010. The results show that discomfort hours are 1112.50 hours in the ASHRAE 55 90% acceptability limits and 865.50 hours in the 80% acceptability limits with solar gains and ventilation being primary reasons. To improve these results, the functional requirements of a new biomimetic adaptable façade are defined as managing and losing light and heat and gaining and exchanging air. Through an investigation from an extensive database of multi-functional mechanisms in nature, the barrel cactus *(Echinocactus grusonii)* is selected as biological inspiration. The expanding dynamic mechanism of the cortex and the dynamic microscopic stomatal openings on the epidermal layer of the stem are translated into a multi-functional biomimetic adaptive façade design. The design is used to replace the façade of the base-case model and an environmental analysis is conducted to demonstrate the improvement. The results show that the total number of discomfort hours with ASHRAE55-2010 Adaptive Thermal Comfort model input are reduced substantially by 51.5% for 90% limits having 540.50 discomfort hours and 67.5% for 80% limits having 282.00 discomfort hours. On the other hand, the total energy consumption shows similar values. The heating load is more than doubled demonstrating that winter comfort levels are dropped slightly with a need for more heating. The improvements in comfort levels are related to warm and hot seasons in a year, ranging from October to April. The next steps for this research are to generate different design options for the façade derived from the same biological principles to identify the most promising biomimetic design strategy.

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References

ABCB, 2018. NCC Volume One. Energy Efficiency Provisions. Handbook (2014). *Australian Building Codes Board*.

Aelenei, D., Aelenei, L. & Vieira, C.P., (2016). Adaptive Façade: Concept, Applications, Research Questions. *Energy Procedia*, 91, pp.269–275. Available at: http://dx.doi.org/10.1016/j.egypro.2016.06.218.

Bar-Cohen, Y. (2005). Biomimetics: Biologically Inspired Technologies. CRC Press, Taylor and Francis Group Publishing, Florida.

Environmental Protection Agency (2009). Sick building syndrome: buildings and their impact on the environment. A statistical summary. Available at: http://www.epa.gov/greenbuilding/pubs/gbstats.pdf. Accessed on 10/05/2018.

Fiorito, F. and Santamouris, M., (2017). High performance technologies and the future of architectural design. *Techne*, 13(August).

Gosztonyi, S., Brychta, M. & Gruber, P., (2010). Challenging the engineering view: Comparative analysis of technological and biological functions targeting energy efficient facade systems. *WIT Transactions on Ecology and the Environment*, 138, pp.491–502.

Health and Safety Executive (1999). Thermal Comfort in Workplace. Guidance for Employers, HSE Books, C250 7/99.

Herrel, A., Speck, T. and Rowe, N. P. (2006). Ecology and Biomechanics: A Mechanical Approach to the Ecology of Animals and Plants. CRC Press, Taylor and Francis Publishing Group, ISBN 9780849332098.

Holmes, M. J. and Hecker, J. N. (2007). Climate change, thermal comfort and energy: meeting the design challenges of the 21st century. Energy and Buildings: 39, 7: 802-814.

Hopkins, W. G. (1995). Introduction to Plant Physiology. John Wiley and Sons, Canada.

Knippers, J. & Speck, T., (2012). Design and construction principles in nature and architecture. *Bioinspir. Biomim. BIOINSPIRATION & BIOMIMETICS Bioinspir. Biomim*, 7(7), pp.15002–10. Available at: http://iopscience.iop.org/1748-3190/7/1/015002.

Lee, J. S., Kuroha, T., Hnilova, M., Khatayevich, D., Kanaoka, M. M., McAbee, J. M., Sarikaya, M., Tamerler, C. and Torii, K. U. (2012). Direct interaction of ligand-receptor pairs specifying stomatal patterning. Genes and Development.

Nobel, P. S. (1988). Environmental Biology of Agaves and Cacti. Cambridge University Press. ISBN-13: 978-0521343220.

Nobel, P. S. and Gibson, A. (1986). The Cactus Primer. Harvard University Press. ISBN-13: 978-0674089914.

Nobel, P.S., 1977. Water relations and photosynthesis of a barrel cactus, Ferocactus acanthodes, in the Colorado desert. *Oecologia*, 27(2), pp.117–133.

Park, C. H., Lee, S. Y., Hwang, D. S., Shin, D. W., Cho, D. H., Lee, K. H., Kim, T., Lee, M., Kim, D., Doherty, C. M., Thornton, A. W., Hill, A. J., Guiver, M. D. and Lee, Y. M. (2016). Nanocrack-regulated self-humidifying membranes. Nature: 532, p. 480-3.

Santamouris, M., Haddad, S., Fiorito, F., Osmond, P., Ding, L., Prasad, D., … Wang, R. (2017). Urban heat island and overheating characteristics in Sydney, Australia. An analysis of multiyear measurements. *Sustainability (Switzerland)*, *9*(5). https://doi.org/10.3390/su9050712.

Stalhberg, R. and Taya, M. (2006). Nastic structures: the enacting and mimicking if plant movements. Biomimetics - Biologically Inspired Technologies, CRC Press, Taylor and Francis Group Publishing, Florida, p. 473-493.

Santamouris et al. (2018). On the energy impact of urban heat island in Sydney: Climate and energy potential of mitigation technologies. Energy & Buildings 166, 154–164.

Santamouris, M. et al., (2017). Urban heat island and overheating characteristics in Sydney, Australia. An analysis of multiyear measurements. *Sustainability (Switzerland)*, 9(5).

United States of America Department of Energy. Commercial Reference Buildings. New construction, primary school. Available at: https://www.energy.gov/eere/buildings/commercial-reference-buildings. Accessed on 11/05/2018.

Von Glasow, R.; Jickells, T.D.; Alexander, B.; Carmichael, G.R.; Church, T.M.; Gallardo, L.; Hughes, C.; Kanakidou, M.; Liss, P.S.; Mee, L.; et al. (2013). Megacities and Large Urban Agglomerations in the Coastal Zone: Interactions Between Atmosphere, Land, and Marine Ecosystems. Ambio, 13, 13–28.