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ORIGINAL PAPER

Biomimetic building facades demonstrate potential to reduce energy consumption for different building typologies in different climate zones

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Abstract

Greenhouse gas (GHG) emissions leading to anthropogenic global warming continue to be a major issue for societies worldwide. A major opportunity to reduce emissions is to improve building construction, and in particular the effectiveness of building envelope, which leads to a decrease in operational energy consumption. Improving the performance of a building's thermal envelope can substantially reduce energy consumption from heating, ventilation, and air conditioning while maintaining occupant comfort. In previous work, a computational model of a biomimetic building façade design was found to be effective in temperate climates in an office context. Through a case study example based on animal fur and blood perfusion, this paper tests the hypothesis that biomimetic building facades have a broader application in different building typologies across a range of climate zones. Using bioinspiration for innovation opens new ideas and pathways for technological development that traditional engineering design does not provide. This study exemplifies the process in a building façade, integrating a new form of insulation, heating and cooling. Methods of mathematical modelling and digital simulation methods were used to test the energy reduction potential of the biomimetic façade was tested in a set of operational applications (office, school, and aged care) and across different climate zones (tropical, desert, temperate, and cool continental). Results indicated that the biomimetic façade has potential to reduce energy consumption for all building applications, with the greatest benefit shown in residential aged care (67.1% reduction). Similarly, the biomimetic building façade showed potential to reduce operational services energy consumption in all climate zones, with the greatest energy reductions achieved in the tropical (55.4% reduction) and humid continental climates (55.1% reduction). Through these results the hypothesis was confirmed suggesting that facades engineered to mimic biological functions and processes can improve substantially decrease building operational energy consumption and can be applied in different building classifications and different climate zones. These results would significantly decrease operational greenhouse gas emissions over the lifetime of a building and provide substantial savings in energy bills. Such facades can contribute to the further reduction in greenhouse gas emissions in a broad range of contexts in the built environment and other areas of technology and design. The flexibility and adaptability of biomimetic facades exemplify how biological strategies and characteristics can augment and improve performance in different environments, since the organisms that inspire innovation are already well-adapted to the conditions on earth. This study also exemplified a method by which other biomimetic building envelope features may be assessed. Further work is suggested to assess economic viability and constructability of the proposed facades.

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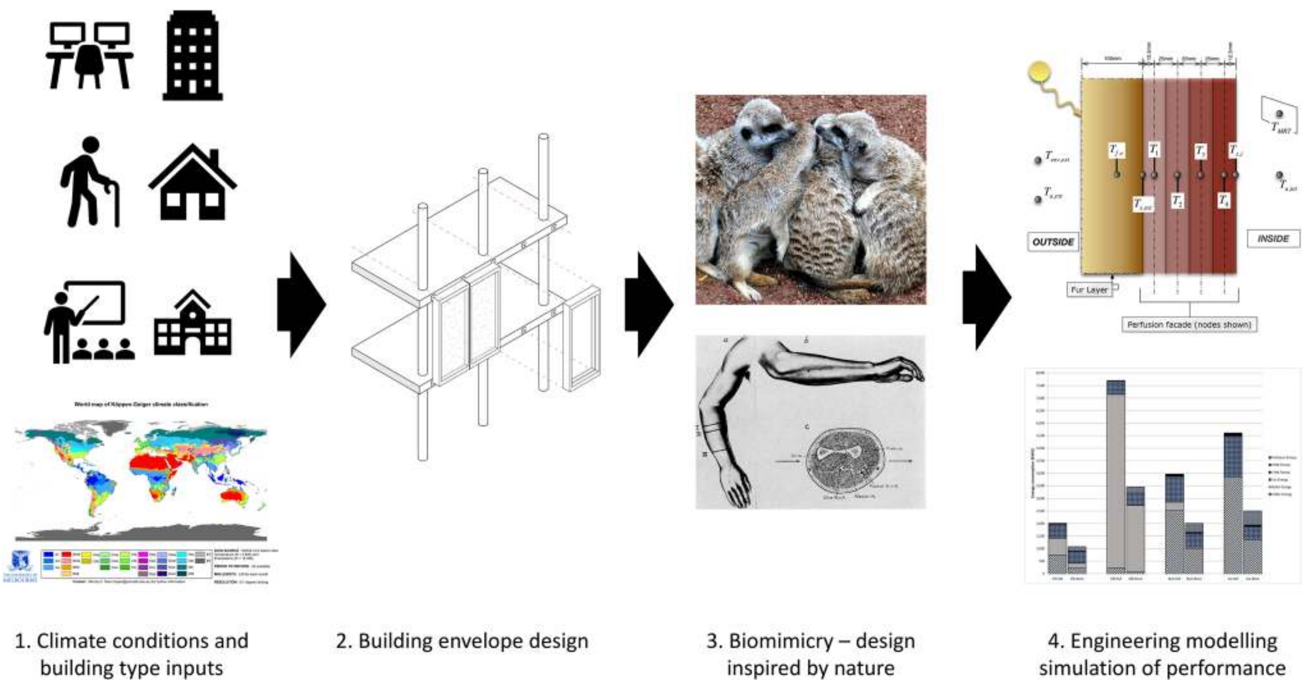
Graphic abstract



Keywords Biomimicry · Adaption · Façade · Bioheat transfer · Nature

Abbreviations

Symbols-Latin

A	Area (m^2)
c_p	Specific heat at constant pressure (kJ kg^{-1} K^{-1})
d_f	Hair diameter (m)
d_t	Simulation timestep (s)
d_x	Simulation spatial step (m)
F_s	Characteristic describing interaction of fur with radiation (–)
H	Height (m)
h	Heat transfer coefficient (W m^2K^{-1})
K	Thermal conductivity (W m^{-1} K^{-1})
k_{eff}	Overall effective thermal conductivity of fur (W m^{-1} K^{-1})
L_f	Fur layer thickness (m)
$N_{f,s}$	Non-dimensional parameter (apparent 'optical thickness' of fur in the solar spectrum) (–)
P	Power delivered (W)
Q, q	Heat transfer (W m^{-2})
q_f	Heat transfer through fur (Wm^{-2})
$q_{e,S}$	Solar radiation absorbed by skin/façade (Wm^{-2})
R	Thermal resistance (m^2K W^{-1})
S	Solar radiation (Wm^{-2})
T	Temperature (K)
T	Time (s)
v	Velocity (ms^{-1})
$\dot{V}$	Volumetric flow rate (m^3s^{-1})
w	Width (m)
$\dot{w}_b$	'Blood' perfusion rate (m^3 m^{-3} s^{-1})
X	*H*orizontal dimension through façade (external surface = 0) (m

Symbols-Greek

α	Thermal diffusivity ($k/\rho c_p$) (m^{-2} s^{-1})
α	Material absorptivity (–)
β_h	Extinction coefficient for fur (infrared spectrum) (–)
$\beta_{h,S}$	Extinction coefficient for fur (solar spectrum) (–)
ε	Material emissivity (–)
ρ	Density (kg m^{-3})
θ_f	Angle between normal to skin surface and hair (°)
θ_S	Angle between normal to the skin and solar direction (°

Subscripts

1, 2, 3, 4	Finite difference node positions
a	Air
amb	Ambient
avg	Average

b	'Blood' (biomimetic façade cooling/heating fluid)
cond	Conduction
conv	Convection
d	Diffuse
e	External
eff	Effective
env	Environmental
f	Fur
g	Ground
i	Internal
i, j, n	Summation indices
lw	Long wave
rad	Radiation
RC	Combined radiation and conduction
s	Surface
S	Solar
skin	Skin
sky	Sky
surf	Surf
T	Total
t	'Tissue' (biomimetic façade material)
u	Unitised façade element
w	Wall

Superscripts

n	Current finite difference timestep

Introduction

There is currently an urgent need to reduce greenhouse gas emissions (GHG) to prevent the worst effects of climate change. In 2018, the International Panel on Climate Change released a special report which updated the probable consequences of global warming and stated that future climate-related risks are greater if warming exceeds 1.5 °C (Hoegh-Guldberg 2018). This report also included a chapter on mitigation pathways to achieve the goal of limiting warming to 1.5 °C. While it is acknowledged that renewable energy sources are crucial to reaching the 1.5 °C target, the IPPC reported indicated that reducing demand in end use sectors would also be important in mitigation strategies—with buildings being a substantial energy consumer. Reductions in energy demand can lead to flexibility in choices available for emissions reduction strategies (Rogelj 2018). Buildings consume a large proportion of the energy required for human activity, and overall account for approximately 19% of the world's greenhouse gas emissions (Residential and Commercial Emissions in the United States 2017; Australian Energy Update 2020; Lucon 2014).

The urgent challenge of reducing energy associated with buildings to reduce carbon emissions includes policy, energy sources, operational energy efficiency, peak energy demand reduction and embodied energy. Studies more broadly on sustainable buildings include Zuo and Zhao (2014) and Hossaini et al. (2015). Net Zero Energy Buildings (NZEBs—buildings that generate sufficient renewable energy on site to meet their energy needs, with net zero greenhouse gas emissions) are an end objective for sustainable buildings. Hu and Qiu (2019) use building simulation methods to conclude that policy-based approaches could achieve net-zero buildings in three countries—China, the USA, and Germany—by 2050. Du et al. (2019) present a study indicating that adoption of prefabrication technologies contribute significant potential for reducing CO2 emissions over the life cycle of residential buildings.

This study focusses on the challenge of improving building operational energy efficiency.

In combination with this carbon reduction and energy efficiency imperative, modern occupant expectation of thermal comfort often requires energy-intensive heating ventilation and air conditioning (HVAC) systems. Widespread adoption of better building practices through design schemes such as Passive House (2020) as well as initiatives such as LEED (USGBC 2020), the Living Building Challenge (Living Building Challenge 2020) and Green Star in Australia (GBCA 2020) have all contributed to improvements in building energy efficiency. The widespread demand and adoption of these rating schemes signifies the demand for the development of initiatives that meet the energy reduction imperative while also maintaining comfort.

Improving thermal performance of building envelopes, including facades, is a key method to reduce building operational energy consumption while providing expected levels of occupant comfort. Historically, humanity has perceived building envelopes as static structures (Knaack et al. 2007). Only relatively recently—in the past half-century or so—have façade-integrated systems been recognised as important factors in reducing building operational energy consumption (Wigginton and Harris 2002), with examples of active and passive façade systems described in Schittich et al. (2006). Other studies to improve façade energy efficiency include: Lee et al. (2002), reviewing high-performance commercial building facades; Al-Hazmy (2006), analysing heat transport through hollow building blocks; Liu et al. (2015) reviewing control strategies for intelligent glazing systems; and He and Hoyano (2010) assessing a passive evaporative cooling wall. Elkhayat et al. (2020) conduct a life cycle assessment of three high-performance glazing systems, Kim and Olsen (2015) report on radiant systems, while Lydon et al. (2017) investigate multifunctional building elements. Porous ceramic materials were tested by He and Hoyano (2010), while novel 'breathing walls' have been proposed by (Craig and Grinham 2017). Examples of active, integrated unitised facades have been constructed, for example, in the Debitel

Headquarters in Stuttgart, Germany (Knaack et al. 2007). Double skin facades have become widespread and tailored to different climates, for example, see Poirazis (2006), Haase (2008), and Hamza (2008). The Ogunmakinde et al. (2021) also note the need for construction materials to fit within a circular economy, such that raw inputs reuse and recycle materials from construction and other industries, and that construction materials can be recycled following dismantling of building assets. Researchers have investigated opportunities to use waste products from other industries, such as insulation from recycled textiles (Islam and Bhat 2019) and waste wool and polyester (Patnaik et al. 2015). Other potential opportunities to improve sustainability of insulation have been reviewed by Asdrubali et al. (2015), including natural and recycled materials. Geopolymer foam concrete, as reviewed by Zhang et al. (2014), also demonstrates opportunities for the integration of sustainable materials in the construction of building facades. Other reviews have focussed on recycled fibres in reinforced concrete (Merli et al. 2020), recycled plastic in concrete (Siddique et al. 2008) and crushed waste glass in construction (Mohajerani et al. 2017).

The increase in active façade installations in buildings is partly due to the developments in the manufacturing industries to support the development of sophisticated components that are required. The advances in electronics and information technology—so-called "Industry 3.0"—allowed the refinement of materials, processes, sensors and controls necessary for successful active façade systems. Currently, there is a shift to "Industry 4.0", originally advocated in Germany. Industry 4.0 advocates the establishment of internal and external cross-linking and digitalisation both within a product life cycle and across different product life cycles. Cross-linking is dependent upon high-quality data collection and analytics, but opens up opportunities for an integrated approach to value chain management and product life cycles, where materials inputs and end-of-life considerations are more readily considered through data sharing and analytics across information networks (Stock and Seliger 2016). A Sustainable Industry 4.0 Framework has been proposed by Kamble et al. (2018), consisting of Industry 4.0 Technologies, Process Integration and Sustainable Outcomes. Similar concepts are derived from the review conducted by Khan et al. (2021). The advantages of these approaches are further enhanced and embedded through "smart" manufacturing process that exploit deep learning based on data representation. This is equally reliant on data input and analysis (Wang et al. 2018).

Alongside developments in active façade technology and, through Industry 4.0, the production capability to fabricate such facades, biomimicry—innovation through natural inspiration—provides additional opportunities for innovation and improvements to building façade performance. The term itself is derived from Greek: 'bio' coming from the Greek 'bios' or life, while 'mimicry' is derived from 'mimesis' meaning imitation (Benyus 1997). By studying natural adaptions, from an ever-growing body of biological knowledge, innovators can extract functional characteristics and translate these characteristics into innovative, adaptive, flexible and more efficient designs. Life has been evolving on earth for over 3.8 billion years and has adapted to changing environmental circumstances (Gordon 1984). Life has, for example, derived high performance materials using common elements (Bhushan 2009). Benyus' contends that biomimicry for innovation follows three axioms "Nature as model", "Nature as measure" and "Nature as mentor" (1997). Pedesen Zari identifies two fundamental approaches in the built environment—defining a human need and investigating how this is achieved in nature, termed "design looking to biology" (2007) and translating a characteristic, species or ecosystem to a human design system—"biology influencing design" (2007). Biomimicry includes aspects of interpretation, adaptation or derivation from biology (Vincent et al. 2006). In modern technology, biomimicry has been shown to be a successful method to engender innovation (Benyus 1997). A systematic approach to biomimicry has been proposed to combine biomimicry with Teoriya Resheniya Izobretatelskikh Zadatch (TRIZ), interpreted as a "Theory of Inventive Problem Solving", which aims to use biomimicry to resolve design challenges and trade-offs (Vincent and Mann 2002). Furthermore, biomimicry has been noted as a pillar to the circular economy (Ogunmakinde et al. 2021).

In the built environment, biological inspiration has influenced architectural design throughout history (Aldersey-Williams 2003; Hersey 1999). However, application in the built environment has tended towards aesthetics and morphology or bio-utilisation (e.g. green walls and roofs). The application of biomimicry to building facades in particular, has been limited to date. Pawlyn (2011) examined biomimetic concepts across architectural disciplines. Gruber (2011) examines the relationships between biology and architecture and the approaches being used to apply biomimicry in architecture. Insect species behaviour (stigmergy) has been aligned with façade-integrated Peltier devices (Bermejo-Busto 2016). In terms of constructed projects exemplifying biomimetic skins, Singapore's *Esplanade—Theatres on the Bay* (DP Architects and Michael Wilford and Partners 2002) resembles the local tropical durian fruit, while the *Kunsthaus Graz* in Austria, by architects Peter Cook and Colin Fournier and consortium ARGE Kunsthaus, 2003, is an organic, biomorphic structure. The One Ocean pavilion in South Korea, by Soma architects in collaboration with Knippers Helbig Advanced Engineering, 2012, is one example where a specific, dynamic, functional characteristic, in this

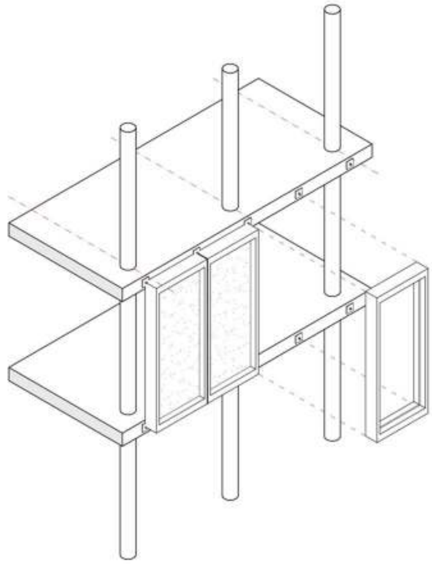
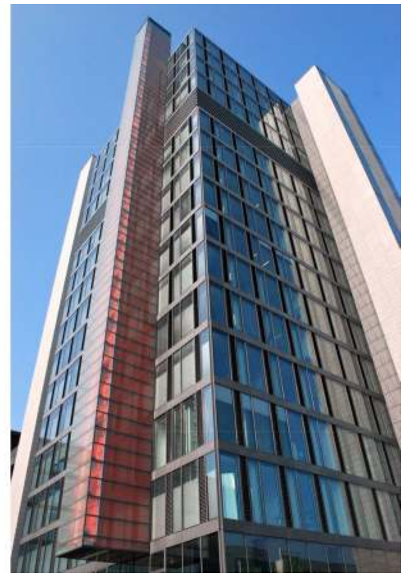



Fig. 1 L: Isometric of unitised façade system (Knaack et al. 2007); R: Debitel headquarters exemplifying unitised façade, Stuttgart (photo by author)

case a mechanism for motion, has been adapted from nature into an active building skin for a project that has reached construction stage.

Badarnah (2012, 2015) proposed a specific conceptual framework for incorporating biomimetic initiatives into building skins including energy and comfort, but also structure, water management, materials and waste. Badarnah (Badarnah 2017) has also presented morphology-based methods for biomimetic façade design. Other researchers to propose schemes for integrating biomimicry to improve the functional performance of building facades include: Al-Obaidi et al. (2017), with a systematic quantitative literature review, Gruber and Gosztonyi (2010), comparing biological skin mechanisms with architectural analogies, Schleicher et al. (2015), conceptualising bio-inspired flexible façade shading schemes, and López et al. (2017), presenting a methodology to collection plant adaptions and guide mapping to architectural designs.

Research by Webb et al. (2013, 2015, 2018); Webb et al. (2011) has shown that specific biomimetic strategies could improve the thermal performance of building envelopes. Testing of the efficacy of the biomimetic design was accomplished through digital modelling and building energy simulation. Others have used the simulation method for assessing building energy consumption. For example, Kumar et al. (2021) use energy simulation to energy performance of residential buildings applying new energy codes Kabul, while Heravi et al. (2020) use simulation as part of an optimisation study into nearly zero energy building's design in developing countries. The methodology in the current study translated biomimetic principles and processes into a heat analysis and energy simulation engine.

Previously, animal fur and blood perfusion were selected as template characteristics for a biomimetic façade design (Webb 2018; Webb et al. 2018). Fur and perfusion were selected for the design based on their effectiveness as strategies evolved by homeothermic mammals to maintain steady core body temperatures in a wide range of environments (Schmidt-Nielsen 1997). Many mammals use a wide variety of hair and fur types to provide insulation, with heat transfer assessments on polar bears (Jessica et al. 2002), the rock squirrel (Walsberg 1988b), wet fur (modelled) (Gebremedhin and Wu 2001), the Harris antelope squirrel and round-tailed ground squirrel (Walsberg 1988a) and a comprehensive study by Liwanag (2008) on fur and blubber in marine mammals.

Digital simulations of biomimetic facades in a unitised façade system (refer Fig. 1 for façade type example) with animal fur and perfusion characteristics were constructed to test the hypothesis that these building envelope features would improve building energy efficiency while maintaining thermal comfort. Simulation results indicated that this façade, based on animal fur and blood perfusion, could be effective in reducing operational energy and peak heating and cooling loads by more than 50% in an office building in a temperate climate of Melbourne, Australia (Webb 2018; Webb et al. 2018). Other researchers have also proposed biomimetic features for building facades, such as Fecheyr-Lippens and Bhiwapurkar (2017) using building simulation to test a high-albedo façade with phase change materials for a small office building in Chicago, USA, with an estimated energy reduction of 68%. Kuru et al. (2018) tested a geometric façade based on ribs and stomatal openings of the barrel cactus on a naturally-ventilated education building in Sydney, Australia, and found a potential improvement by 51.5% for the thermal comfort acceptability. Park (2016) introduced biomimetic strategies based on reflecting superposition eyes to improve functional

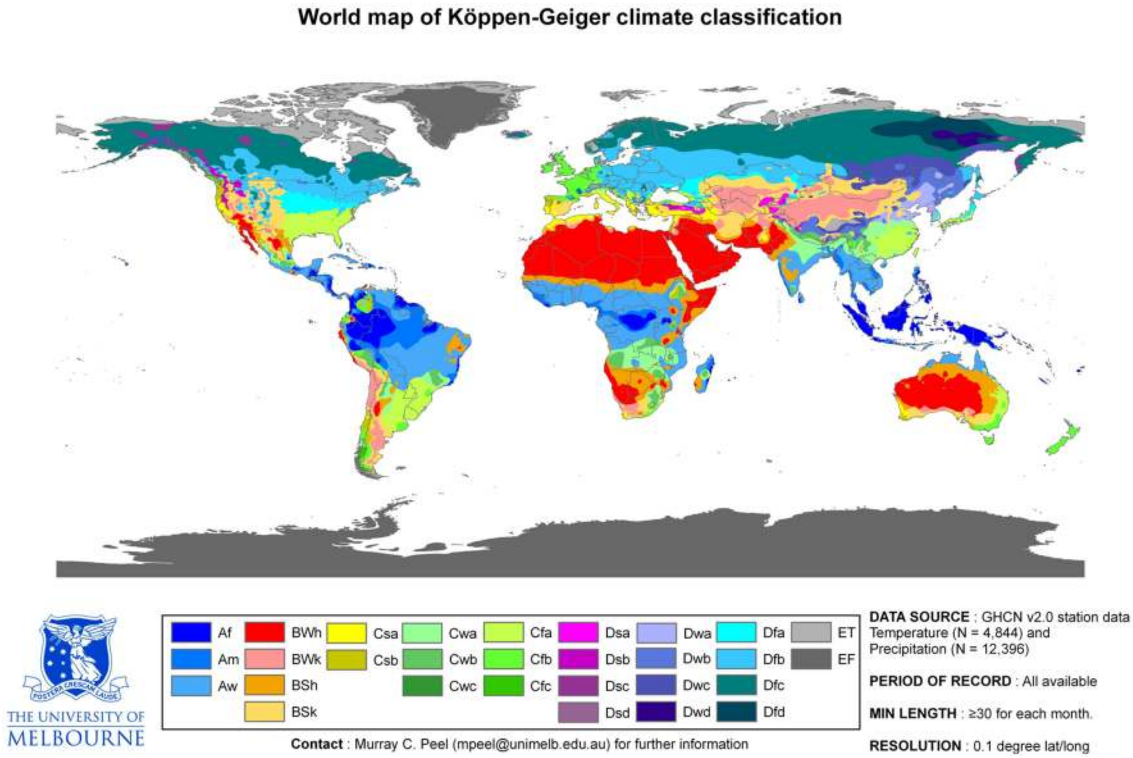


Fig. 2 Köppen–Geiger climate map of the world (Peel et al. 2007)

illuminance in sports stadiums in Incheon, Korea. Craig et al. (2008) proposed a cellular structure with thermal mass as a roof cooling mechanism in Riyadh, Saudi Arabia, using TRNSYS to demonstrate a 4.5 °C reduction in roof temperature.

However, testing of the fur and perfusion façade, and these other case studies, have been limited to a singular test case for one building typology in individual climate zones. Research has been limited on wider application of biomimetic façade initiatives for building facades. For more widespread application, it was important to test the efficacy of biomimetic façade designs in different building types and in different climate zones. The hypothesis in this study was to assess whether biomimetic building facades, based on their energy-reduction potential, have a broader application. A case study was proposed to test whether a biomimetic building façade, based on animal fur and blood perfusion, would be as effective at improving energy efficiency in different climate zones and on different building types as it was shown for one building typology (office) in a temperate climate. The confirmation or rejection of this hypothesis would indicate whether biomimetic facades could be successful in broader applications, rather than individual projects. The study also aims to demonstrate suitable methods for assessing biomimetic initiatives through mathematical modelling and building simulation.

Materials and methods

As indicated in Sect. 1, the objective of this expanded study was to determine whether the animal fur-perfusion façade design was at least as effective in a broader range of climate zones and building types as it was shown for an office building in a temperate climate.

A conventional method to distinguish climate zones is the Köppen–Geiger (K–G) climate classification, refer Fig. 2 (Peel et al. 2007). This study would test the animal fur-perfusion façade in four very different climate zones:

- Temperate oceanic (Cfb)
- Hot desert (Bwh)
- Tropical savannah (Aw)
- Humid continental (Dfb)

Furthermore, the study examined the effectiveness of the fur and perfusion biomimetic building facade in a set of three different operational applications:

- Office buildings,
- School buildings, and
- Aged care facilities.

The method for the assessment of the fur and perfusion biomimetic façade for different climate zones and building types could be summarised as follows, with section references for descriptions of detailed methods, inputs and assumptions:

- Section 2, Materials and Methods
    - Section 2.1, Façade Model Development. Using the methods developed previously (Webb 2018; Webb et al. 2018), heat and energy transfer models were created to represent building facades.
    - A model was constructed for a conventional static façade composed of lightweight construction materials (reference façade) to act as a baseline for comparison to the biomimetic designs in terms of heat transfer and annual energy performance.
    - Biomimetic façade models were constructed. The equations for an external fur layer and a perfusion layer within the façade were included to represent the insulation influence of the fur and fluid heat transfer effects (refer Sect. 3).[1]
    - Section 2.2, Dynamic Building Simulations. Reference and biomimetic façade models were integrated into to a conventional Building Energy Simulation (BES) software package to test the performance of the proposed biomimetic façade designs.
- Section 3, Results and discussion
    - Section 3.1—Extent of simulations, where the format of the simulations was described.
    - Section 3.2—Results for the façade scenarios in the selected climate zones were summarised and discussed.
    - Section 3.3—Results for the façade scenarios for the three selected building types were summarised and discussed.
    - Section 3.4—Comparison with simulation and Energy Reduction Studies. The results obtained in the current study were compared with a selection of alternative energy efficiency measures for different climate zones building types.

[1] Through the use of two separate modelling pathways, both using physically valid methods of solution, the biomimetic façade models were previously verified as accurate and consistent with physically viable results (Webb 2018).

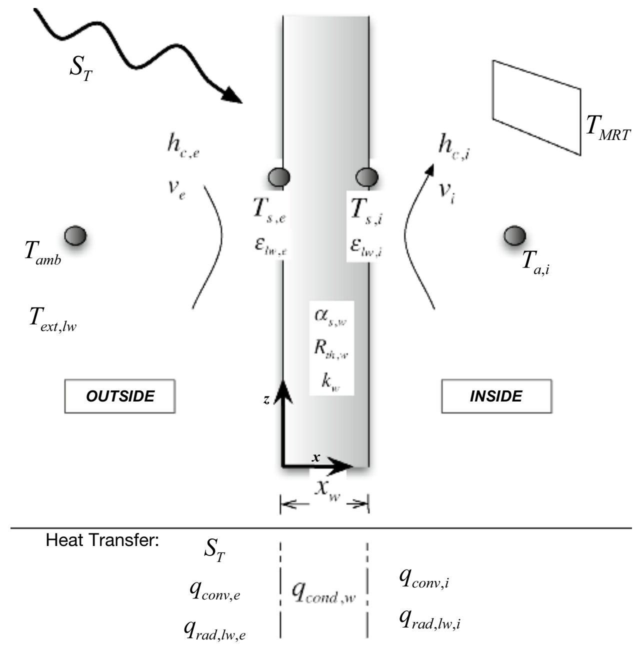


Fig. 3 Representation of planar façade

- Section 4, Limitations and further work
    - The limitations in the methods used in this study were identified and examined.
    - Economic impact was discussed.
- Section 5, Conclusions
    - The conclusions for the study were drawn, including whether the results confirmed the hypothesis described in Sect. 1.

Façade model development

The façade models for conventional materials and the biomimetic fur and perfusion facades are summarised below. For full model development, refer to Webb (2018) and (Webb et al. 2018).

Reference

For the Reference Façade (Ref), a time-dependent model was developed based on the generalised 1-D heat equation through a plane wall without sources or sinks (Holman 2001). The temperature, $T(x,t)$, was calculated as:

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha_w}\frac{\partial T}{\partial T} \quad (1)$$

The physical situation is represented in Fig. 3. A heat balance at the inside and outside surfaces was conducted to define the internal and external boundary conditions.

For the external surface:

$$S_T + q_{rad,lw,e} = q_{conv,e} + q_{cond,w,e} \tag{2}$$

These heat balance boundary conditions were expanded to include relevant coefficients and temperatures:

$$\begin{aligned} -k_w \frac{\partial T}{\partial x}\Big|_{x=0} &= q_{cond,w,e} \\ &= \alpha_{s,w}S_T + \left(h_{c,e} + h_{rad,lw,ext}\right)\left(T_a - T_{s,e}\right) \\ &\quad + h_{rad,lw,g}\left(T_g - T_a\right) + h_{rad,lw,sky}\left(T_{sky} - T_a\right) \end{aligned} \tag{3}$$

Radiant heat transfer coefficients were linearized, e.g. for long wave radiation:

$$h_{rad,lw,e} = \frac{\varepsilon_{rad,lw}\sigma\left(T_a^4 - T_{s,e}^4\right)}{T_a - T_{s,e}} \tag{4}$$

A similar heat balance was conducted for the inside surface:

$$q_{cond,w} = q_{conv,i} + q_{rad,lw,i} \tag{5}$$

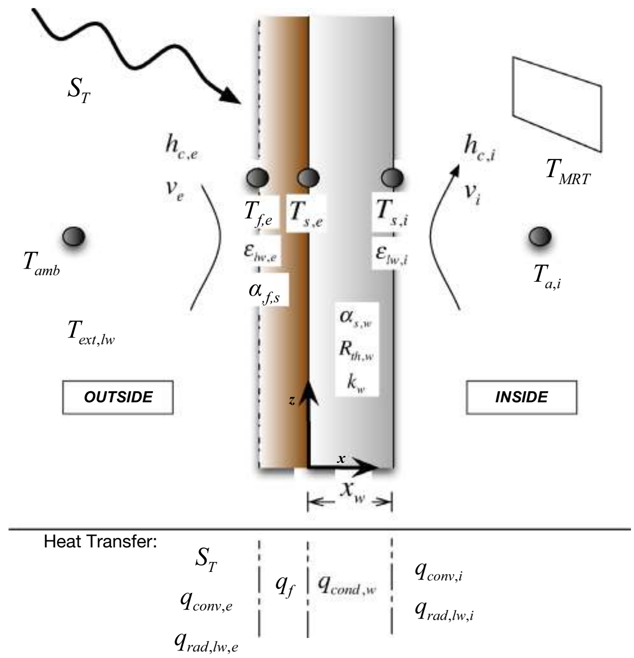


Fig. 4 Façade model with external fur lining

External fur layer

Multiple models and methods have been devised to calculate heat transfer through fur or, equivalently (refer Webb (2018); Webb et al. (2011)). The Davis and Birkebak (1974) model was selected for translation to a fur-lined biomimetic façade design. This model related conductive energy flux across the fur layer, q_f, to a temperature gradient, ΔT, and fur thickness layer, L_f, via an effective fur thermal conductivity, k_{eff}, as follows:

$$q_f = k_{eff}\frac{\Delta T}{L_f} \tag{6}$$

Further development on the radiation heat transfer using an extinction coefficient and energy relationships let to the following expression:

$$q_f = \frac{k_{eff}}{L_f}(T_{s,e} - T_{f,e}) + \left(1 - \frac{cos\theta_S}{N_{f,S}F_S}\right)q_{S,skin} - \frac{\alpha_{f,S}S_T cos^2\theta_S}{N_{f,S}F_S} \tag{7}$$

where: $\alpha_{f,S}$ = bulk fur solar absorptivity, $q_{S,skin}$ = solar radiation absorbed by skin, F_S = absorption factor at solar wavelengths, $N_{f,s}$ = optical thickness for solar wavelengths (Webb et al. 2018), $\beta_{h,S}$ = hair extinction coefficient across solar wavelengths (Davis and Birkebak 1974).

With an expression for heat transfer through the fur layer, q_f, the fur heat transfer was integrated into the façade model (Fig. 4). Heat transfer through the fur was then incorporated into a heat balance on the external surface of the wall:

$$S_T + q_{rad,lw,e} = q_{conv,e} + q_{cond,w,e} \tag{8}$$

Following the solar heat transfer model developed for the reference, this became (refer Fig. 3):

$$\begin{aligned} q_f &= \alpha_{s,w}S_T + (h_{c,e} + h_{rad,lw,ext})(T_a - T_{s,e}) \\ &\quad + h_{rad,lw,g}(T_g - T_a) + h_{rad,lw,sky}T_{sky} - T_a \end{aligned} \tag{9}$$

Perfusion layer

Pennes (1948) provided a fundamental basis for the study of heat transfer in living tissue, which was selected as the basis to describe fluid perfusion in the biomimetic façade model as follows (refer Fig. 5 and Webb et al. (2018)):

$$k_t\frac{\partial^2 T}{\partial x^2} + \rho_b c_{p,b}\dot{w}_b(T_{ao} - T) = \rho_t c_{p,t}\frac{\partial T}{\partial t} \tag{10}$$

Equation (10) could be solved in place of the unmodified heat equation (Eq. (1)) as the basis for perfusion in the biomimetic façade design.

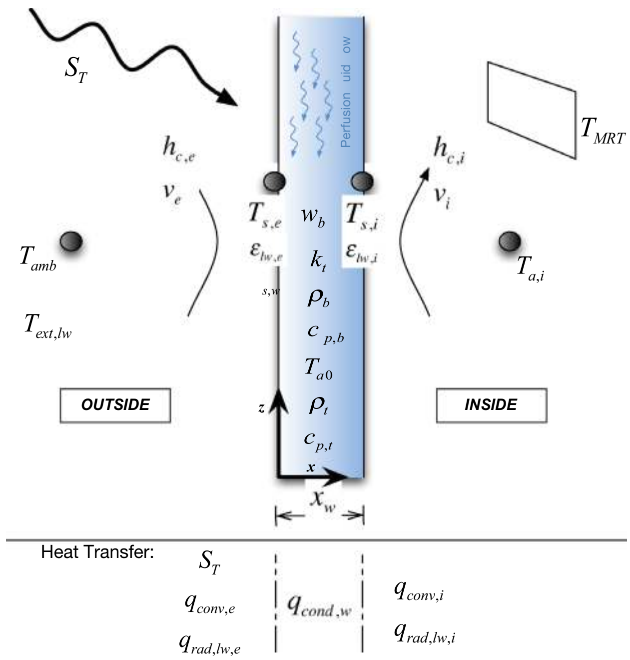


Fig. 5 Façade model with internal perfusion

Finite difference solutions

The equations in the preceding sections required suitable solution methods for adoption in a dynamic building annual energy simulation. This led to the introduction of a finite difference scheme to numerically solve the model equations (Webb 2018; Webb et al. 2018). An explicit finite difference scheme was developed for the biomimetic façade, with the nominal 0.1-m-thick façade split into four discrete steps. Accordingly, the fundamental heat equation, Eq. (1), became:

$$T_i^{n+1} = Fo\left[T_{i-1}^n - (2 - \frac{1}{F_0})T_i^n + T_{i+1}^n\right] \tag{11}$$

Here, T_i represented the temperature for the *ith* internal node at timestep $n + 1$ and the Fourier number, Fo, is:

$$Fo = \frac{\alpha_w \Delta t}{\Delta x^2} \tag{12}$$

The finite difference models for the reference and biomimetic facades are shown in Fig. 6.

Dynamic Building simulations

Customised finite difference models were developed in the preceding section, representing the characteristics of both conventional and biomimetic façades. These numerical models were implemented in TRNSYS for annual dynamic energy simulation. The biomimetic design model adapted for TRNSYS software in this study was a façade that included both fur and perfusion initiatives, i.e. it included the advantages of both. TRNSYS (TRaNsient SYstem

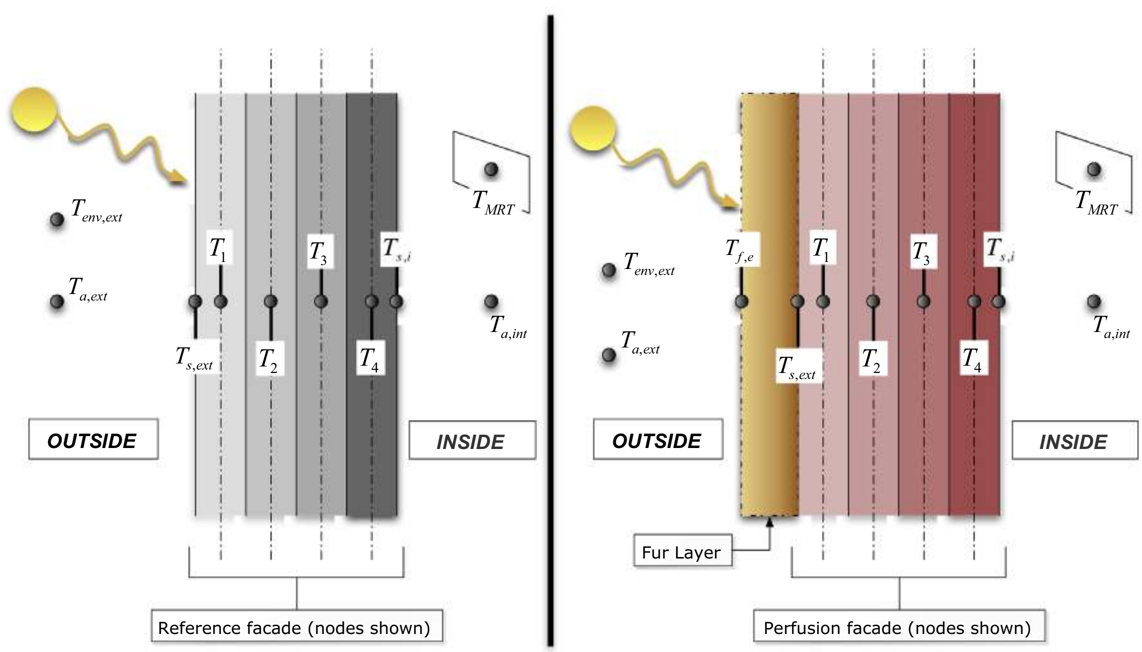


Fig. 6 Finite difference façade models: reference (L) and biomimetic (R)

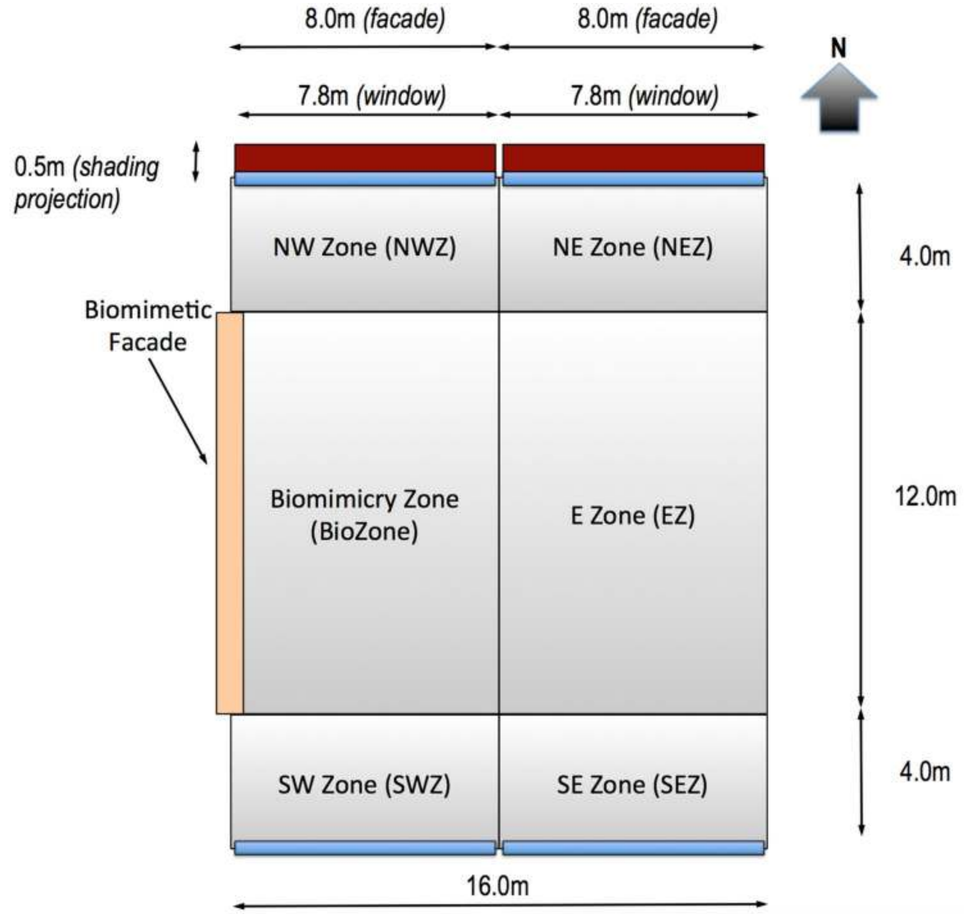


Fig. 7 Type 56 office model: floor plan and separate thermal HVAC zones

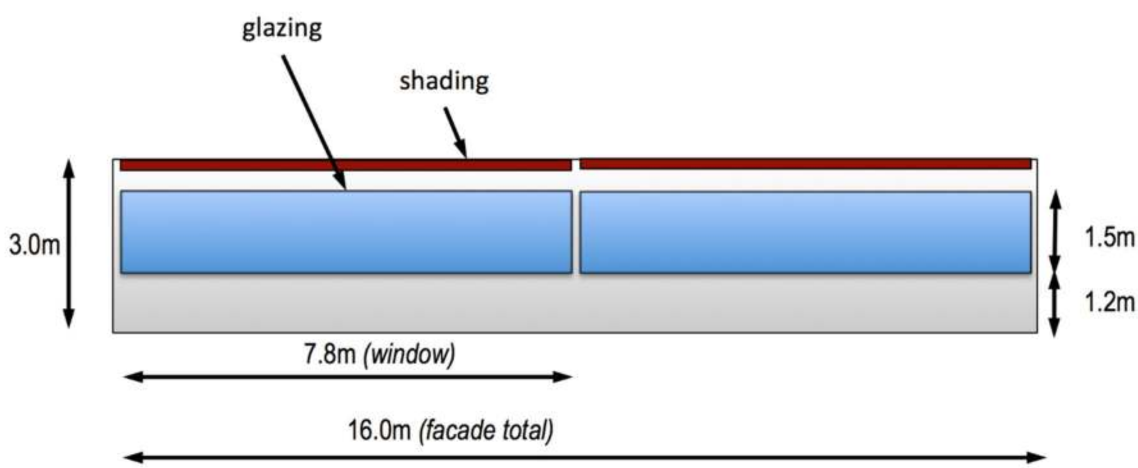


Fig. 8 Type 56 office model: north elevation

Simulation or TRNSYS) is a well-recognised method for testing building designs (refer validation standard and (*ASHRAE 140–2017*) and Neymark and Judkoff (2008)).

Building Simulation model

In all climates selected, a rectangular floor plate was created, containing six zones, with glazing north and south facades (Figs. 7 and 8). The model assumed that the

Table 1 TRNSYS model building fabric

Element	Description	Thickness (m)	Thermal resistance ($m^2K\ W^{-1}$)
Walls	Lightweight metallic façade with EPS insulation	0.104	2.93
Floor	Concrete slab with air gap and ceiling tile below	0.228	1.15
Roof	Metal deck with glass wool batt insulation and ceiling plenum above acoustic tile	0.134	5.43
Internal partitions (between zones)	Gypsum plaster stud walls (no insulation)	0.090	0.48
		SHGC (–)	Thermal transmittance ($W\ m^{-2}\ K^{-1}$)
Glazing	Double: 8.38 mm Neutral Comfortplus-12 mm air-6 mm EnergyTech Clear	0.400	1.70
Frame (10% of window area)	Standard aluminium	0.450	12.50

*SHGC = Solar heat gain coefficient

building floor was situated above another floor of identical dimensions (creating an adiabatic floor surface), while the ceiling was externally exposed above via an external roof construction.

Building fabric

Building fabric and glazing for the Type 56 model are shown in Table 1.

HVAC system

The occupied zones on the modelled building floor were assumed to be air conditioned to meet thermal comfort requirements of occupants during hours of operation, which depended upon the building type, as per Table 2. The occupancies for each building type were based on standard assumptions regarding occupancy of the three classes of building. It is acknowledged that the Covid 19 Pandemic may lead to long term changes in office building occupancy. However, the schedules used in the modelling remain the standard profiles in assessing building energy consumption and form the main tool for comparison of energy-saving designs for buildings.

HVAC system design calculations were based on an assumption that the building would be serviced by a chilled water (CHW) and heating hot water (HHW) variable air volume (VAV) air conditioning system for both heating and cooling. Air would be cooled or heated via chilled or heating hot water. The following major components were required:

- Chiller (assumed air-cooled, Integrated Part Load Value of 3.7),
- Boiler (assumed gas-fired, efficiency 80%),
- Fans,
- Chilled water pumps,
- Hot water pumps for heating.
- Outside at 11 L s^{-1} per person (Schittich et al. 2006).

The development of the specific pressures and capacities of HVAC equipment was as per Webb (2018). These were based, where possible, on minimum energy efficiency standards (National Construction Code BCA 2016 *Volume 1* 2016).

Internal loads and schedules

Three customary internal heat gains were added to the model: occupants, lighting, and electrical equipment (computers, printers, monitors, refrigerators, etc.). Lighting was specified as per the maximum lighting efficiency

Table 2 HVAC Schedule for each building class

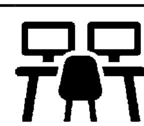
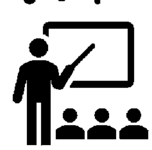
Building class		HVAC daily operation
Office		08:00–18:00
Aged care		0:00–24:00 (24 h)
School		08:30–15:30

Table 3 Internal loads for building classes

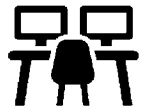
Building class		Occupants	Lighting (W m^{-2})	Equipment (W m^{-2})	Activity level (met)
Office		1 per $10m^2$	9	11	1.2
Aged care		1 per $20m^2$	7	5	0.8
School		1 per $2m^2$	8	5	1.2

Table 4 Performance measures for detailed analysis

Primary performance measures	Units
Biomimetic zone annual HVAC energy consumption	kWh
Peak façade heat loss or gain	W

allowance given in the National Construction Code BCA 2016 *Volume 1* 2016). For offices, equipment heat gains were set to the specifications of NABERS Ratings for offices (Handbook for estimating NABERS Ratings 2019). For aged care, internal heat gains were set on the assumption that aged care facilities would have minimal equipment and account for items such as a computer terminal and TV, while school classrooms were also assumed to have minimal equipment loads (it was assumed that each student did not use a laptop).

Metabolic and clothing values were referenced from the data in the ASHRAE Handbook - Fundamentals 2009). A lower value of activity was ascribed to occupants in Aged Care buildings. Clothing was maintained consistently across all three cases and set at 0.6 clo (summer) and 0.95 clo (winter). The following Table 3 summarises these inputs.

Performance metrics

Building facades perform numerous functions; however, the primary measures for evaluating the effectiveness of the biomimetic facades in this study were the minimisation of building HVAC energy consumption and minimisation of peak façade heat loss and gain, as shown in the Table 4.

In addition to these energy-based criteria, it was also necessary to define 'thermal comfort' in measurable terms (Schittich et al. 2006):

- Indoor Air Temperature (IAT)—20–25 °C, and
- Mean Surface Temperature (MST)—no more than 3 °C different to air temperature.

Results and discussion

Using models for conventional and biomimetic facades described, integrated into a building model in TRNSYS (Sect. 2), annual simulations for the different climate zones and building typologies were conducted. The results for these simulations in terms of annual operational services energy and peak loads are presented herein.

Table 5 Climate simulations

K-G climate classification	Climate classification description	Example location	Simulations	
			Biomimetic (Biom)	Reference (Ref)
Cfb	Temperate oceanic	Melbourne, Australia	Cfb Biom	Cfb Ref
Dfc	Hot desert	Bechar, Algeria	Dfc Biom	Dfc Ref
Bwh	Tropical savannah	Manilla, Philippines	Bwh Biom	Bwh Ref
Aw	Humid continental	Stockholm, Sweden	Aw Biom	Aw Ref

Table 6 Building type simulations

Building type		Example location	Climate description	Simulations	
Name	Abbreviation			Biomimetic (Biom)	Reference (Ref)
Office	Ofc	Melbourne, Australia	Temperate	Ofc Biom	Ofc Ref
Education	Edu	Melbourne, Australia	Temperate	Edu Biom	Edu Ref
Aged Care	AgdCr	Melbourne, Australia	Temperate	AgdCr Biom	AgdCr Ref

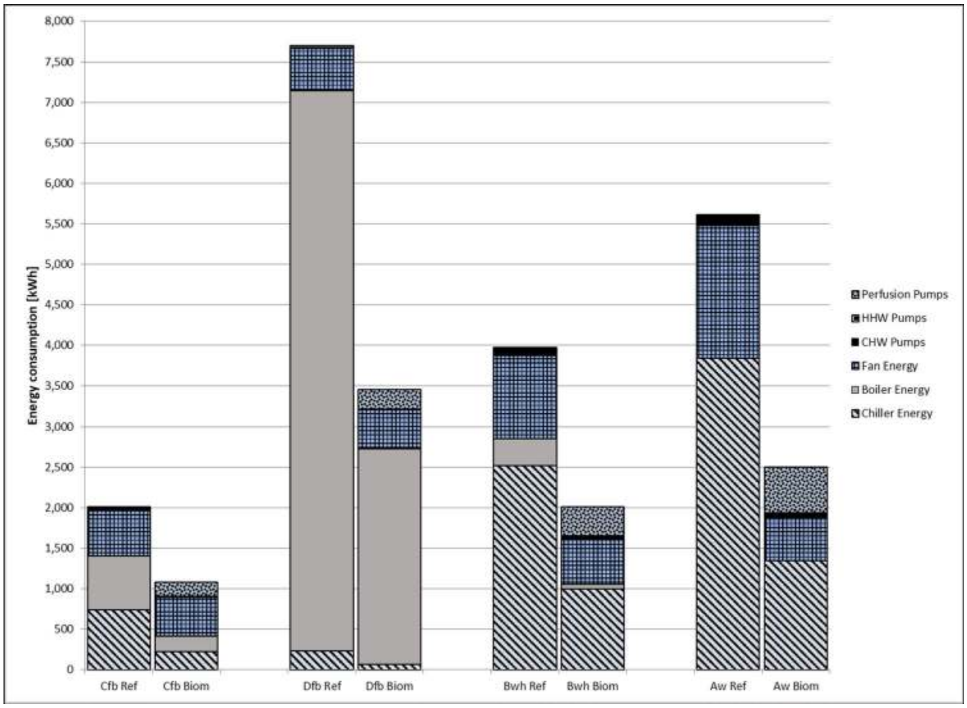


Fig. 9 Annual energy for different climates—comparison

Extent of simulations

For each of the four climate zones, an annual dynamic energy simulation was conducted for both the biomimetic façade ('Biom') and the reference façade ('Ref') as indicated in the following Table 5.

For each of the three building types, an annual dynamic energy simulation was conducted for both the biomimetic façade ('biom') and the reference façade ('ref') as indicated in the following Table 6.

Climate zones

Annual energy comparison: climate zones

The following charts display annual energy results for the four climate zones for the biomimetic zone only (refer to Fig. 7). This allowed the analysis to focus on the performance of biomimetic facade and to reduce complexity in the presentation of the results. Figure 9 displays results of annual services energy consumption for each of the climate simulations with the biomimetic façade, including reference cases. Table 7 provides a summary of all the results across the different climate zones while Table 8 indicates the reduction that each biomimetic design achieved.

Figure 9 shows that the temperate oceanic climate zone (Cfb)—the baseline case—required least energy overall to maintain comfort conditions for occupants. As expected, more extreme climate cases required additional energy to maintain the comfort band of 20–25 °C. Stockholm (Dfb), at a latitude of 56.3°N latitude, consumed the most energy, largely due to a significant proportion of heating and very limited cooling. Contrastingly, Béchar (Bwh, 31.6°N) and Manila (Aw, 14.6°N), much closer to the equator, consumed more energy that the baseline Cfb case, due primarily to an increase in cooling requirements. The cooling demand (as indicated by the chiller energy) was six times greater than the baseline Cfb case. It was observed that the greatest cooling demand occurred in the Manila simulation (Aw), which also demanded additional cooling from the perfusion pumps.

Reviewing the comparative results, biomimetic cases outperformed the reference cases in all climate zones. Physical

Table 7 Energy consumption for climate zones

Energy category	Temperate oceanic		Humid continental		Hot desert		Tropical savannah	
	Cfb Ref	Cfb Biom	Dfb Ref	Dfb Biom	Bwh Ref	Bwh Biom	Aw Ref	Aw Biom
Chiller energy	741	222	228	61	2514	998	3841	1349
Boiler energy	665	188	6914	2668	339	60	0	0
Fan energy	571	487	527	482	1019	548	1637	527
CHW pumps	30	10	9	2	92	44	136	61
HHW pumps	2	1	20	8	1	0	0	0
Perfusion pumps	0	173	0	237	0	358	0	566
Total	2008	1080	7698	3457	3965	2008	5615	2503

Table 8 Biomimetic design reductions in energy in each climate zone

Energy category	Temperate oceanic (Cfb Biom) (%)	Humid continental (Dfb Biom) (%)	Hot desert (Bwh Biom) (%)	Tropical savannah (Aw Biom) (%)
Chiller energy	– 70	– 73	– 60	– 65
Boiler energy	– 72	– 61	– 82	na
Fan energy	– 15	– 9	– 46	– 68
CHW pumps	– 68	– 74	– 53	– 55
HHW pumps	– 72	– 61	– 82	na
Perfusion pumps	na	na	na	na
Total	– 46.2	– 55.1	– 49.4	– 55.4

characteristics of the fur lining to provide extra insulation and a barrier to incoming solar radiation, in combination with the water-based perfusion inside the façade, were effective in improving the building envelope energy efficiency. Absolute energy savings for the more extreme climates (Dfb and Aw) were the greatest. The reference case for Stockholm (Dfb) was 4241 kWh greater than the biomimetic design, while in the Manila simulation, the reference was 3112 kWh greater than the biomimetic design. The baseline Cfb case showed 928 kWh difference between reference and biomimetic designs. However, in *proportional* terms for total energy, the variations between biomimetic and reference cases across the climates zones were actually similar. The baseline Cfb case showed a 46% reduction in total energy savings, and all of the other three cases indicated a proportional decrease within 10% of this figure. This indicated that the biomimetic façade would have a similar effect across different climate zones (at least for those tested).

Observing individual services energy components, in all cases the biomimetic design had a lower energy consumption compared to the reference case. There was more proportional variation between cases than comparing total annual energy, For example, there was a 68% reduction in fan energy for the Aw (tropical) case, while just a 9% reduction in fan energy for the Dfb (colder humid continental) case. Conversely, chilled water pump demand in the Aw case was substantially higher than in the other climates (both biomimetic and reference simulations). This was likely due to the high, and almost continuous cooling demand requirements in a topical climate. The added insulation provided by the fur-lined façade provided a barrier to the external weather, but with small diurnal fluctuations and constant infiltration, the extra insulative effect was diminished, especially without the opportunity to obtain free cooling from cooler outside air temperatures during some parts of the day. This result pointed towards a more general trend indicating that additional energy-saving initiatives, other than improvements in the building envelope, must be considered to minimise overall building services energy consumption.

In this study, it was assumed that the energy source for heating was natural gas-fired boilers. However, given the accelerating impacts from climate change and the improvements in the technology, electric heat pumps have become more favourable as a heating source. Electric heat pumps have a COP range from 3.2 to 4.5. Therefore, an alternative scenario was tested where the heat source was assumed to be an electric heat pump with a COP of 3.2. In this instance the corresponding energy results appeared markedly different, as shown in Fig. 10. Under these conditions, the only remaining climate with a proportionally significant heating consumption was the Dfb (humid continental) case. The

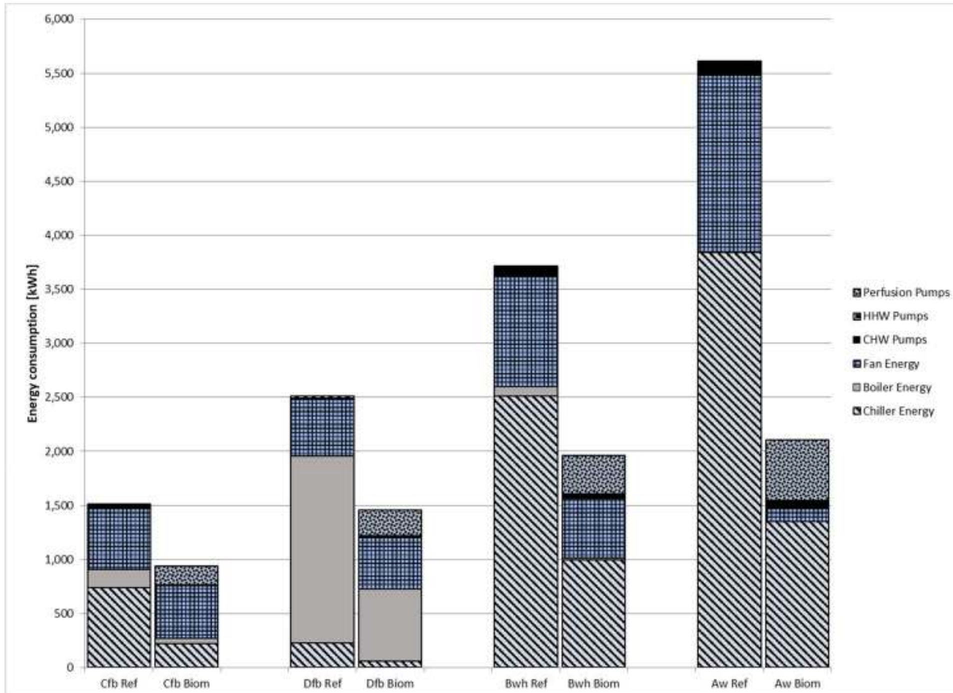


Fig. 10 Annual energy for different climates—heat pump

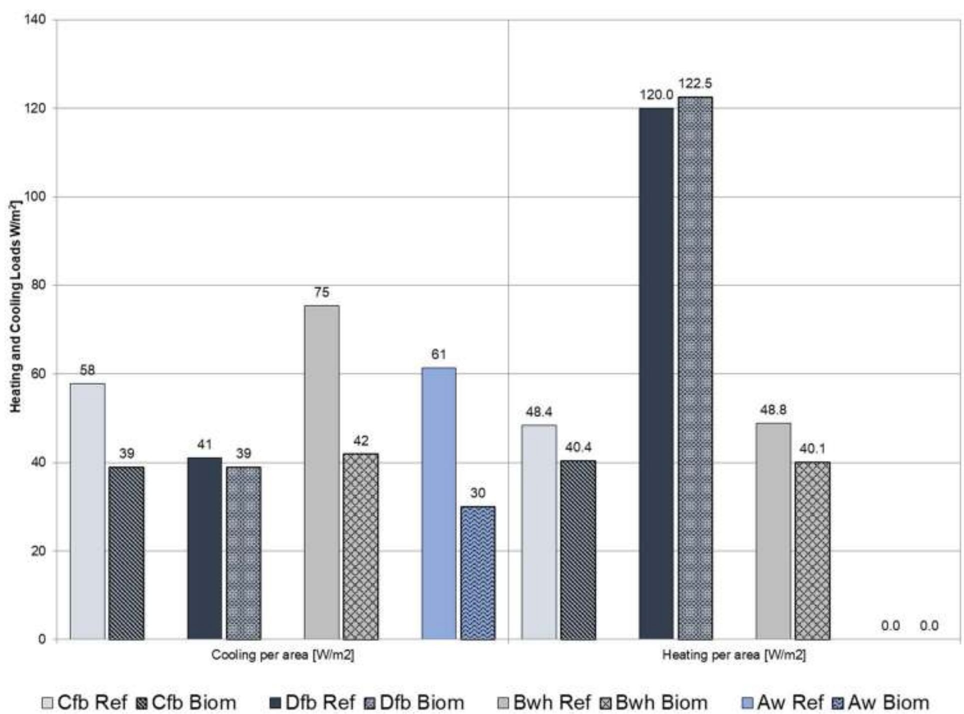


Fig. 11 Peak heating and cooling for different climates—comparison

tropical Aw location now consumed the greatest annual building services energy, with a large margin between the reference Aw (tropical) case and the Bwh (hot desert) case (34% difference). The difference in the biomimetic cases was not as pronounced (22% difference). Even considering these variations from the gas-fuelled heating, it was clear that the biomimetic designs provided a substantial improvement in energy efficiency.

Peak heating and cooling comparison: climate zones

Peak heating and cooling results were compiled for the biomimetic zone. These loads represented the maximum annual

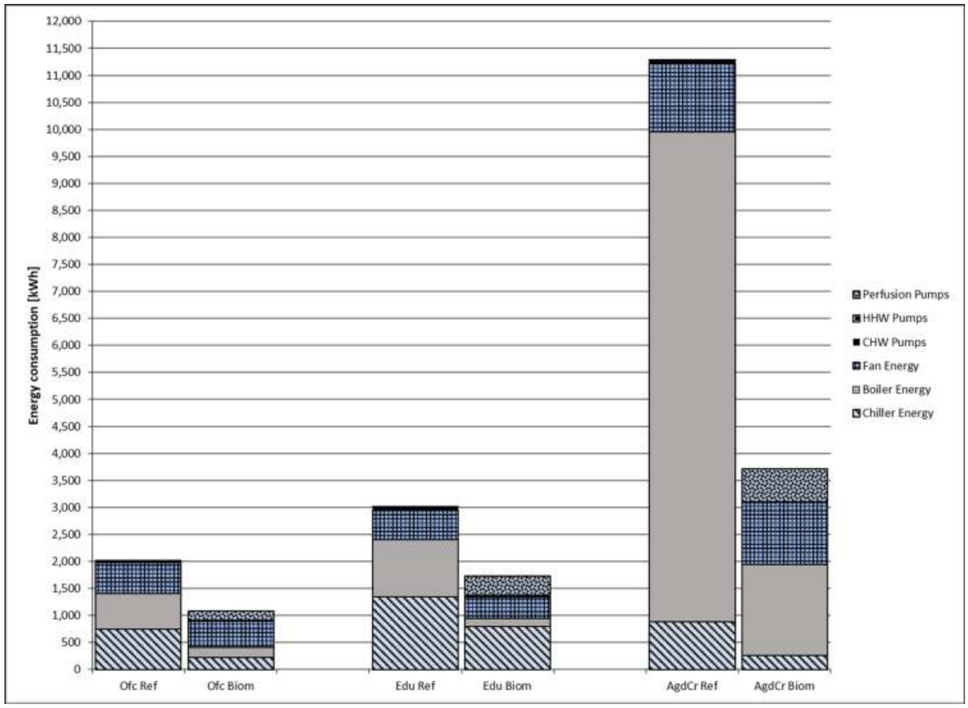


Fig. 12 Annual energy for different building types—comparison

cooling and heating demand that was required for the space, throughout the year, normalised by floor area. The following charts indicate how the biomimetic facades performed in each of the climate zones with respect to peak heating and cooling loads. Figure 11 shows peak heating and cooling loads for the simulations with the biomimetic façade, including reference cases.

Reviewing the results for peak loads, there were similarities and differences across climate zones. In peak cooling, simulated peaks were similar for the biomimetic zones in three of the cases (Cfb, Dfb and Bwh), while the Aw (tropical) climate showed the lowest peak cooling demand. This was despite the tropical climate having the greatest annual cooling demand and again indicated the continuous nature of the cooling requirements in tropical climates. There was greater differentiation in the heating demand across climate zones, with the Cfb and Bwh zones having a similar peak demand, while the coldest climate had a demand that was three times greater than these cases. It was important to also note that peak loads presented here represent peak system requirements to meet the *dynamic* cooling or heating demand for the simulated annual weather file, and would differ from the *design* heating and cooling loads as calculated by a mechanical design engineer.

Comparing relative differences between the biomimetic designs and reference cases in each climate, the greatest reduction achieved was for cooling in the Aw climate, which can be attributed to the effect of perfusion cooling present in the biomimetic façade. The perfusion cooling made a substantial contribution to the overall cooling supply, reducing the requirement for air-based cooling that was required in the Aw reference case. In the Aw biomimetic case, efficiencies were obtained through water-based cooling, low volumes of water required (compared to an air-based solution) plus a reduction in the fan energy required to deliver cooling to the occupied zones. In the Dfb case—a much colder climate—there was a much smaller difference between reference and biomimetic cases for heating and cooling. The heating demand for the biomimetic case was actually greater in the Dfb case. This was due to the additional heating supplied by the perfusion system in the simulation, which would have provided additional heating to the space but also lost heat to the external environment, leading to a 2% increase in peak simulated heat demand. One potential option to reduce heat loss from perfusion would be to introduce an additional layer of solid insulation beneath the external fur layer, directing greater heat flow to the internal surface.

Building types

Annual energy comparison: building types

Similar to climate simulations, the building type comparison shows annual energy results for the biomimetic zone only. Figure 12 displays results for the annual services energy consumption for each of the building type simulations with the biomimetic façade, including reference cases. Table 9 provides a summary of all the results across the different building types, and Table 10 shows the reduction that each

Table 9 Energy consumption for building type simulations

Energy category	Office		Education		Aged care	
	Ofc Ref	Ofc Biom	1342	792	AgdCr Ref	AgdCr Biom
Chiller energy	741	222	1065	155	886	256
Boiler energy	665	188	543	392	9064	1690
Fan energy	571	487	54	35	1276	1140
CHW pumps	30	10	3	0	36	11
HHW pumps	2	1	0	353	26	5
Perfusion pumps	0	173	3007	1727	0	607
Total	2008	1080	1342	792	11,288	3709

Table 10 Biomimetic design reductions in energy for each building type

Energy category	Office (%)	Education (%)	Aged care (%)
Chiller energy	− 70	− 41	− 71
Boiler energy	− 72	− 85	− 81
Fan energy	− 15	− 28	− 11
CHW pumps	− 68	− 35	− 69
HHW pumps	− 72	− 85	− 81
Perfusion pumps	na	na	na
Total	− 46.2	− 42.6	− 67.1

biomimetic design had over its respective reference case for each different building type.

Following the trend of the climate simulations, biomimetic designs showed reductions in the services energy across the three building types. Compared with the varied energy reductions across climate categories, the reductions in energy for each of the services components (cooling, heating, etc.) were similar between building types. There was one exception, however: the heating energy consumption for the Aged Care simulation, which showed a 7374 kWh reduction from the reference case, compared with less than 1000 kWh reduction in the Education and Office simulations. The main contributing factor to this result is the extended operational schedule for Aged Care facilities, which run 24 h per day and require constant conditioning for residents—particularly for heating results in a temperate climate. Therefore, the improved insulation benefits of the fur-lined façade had a greater impact. Apart from in heating energy, the absolute reductions in energy were similar, for fans, chillers and pumps.

In terms of a proportional comparison, the reductions observed for the biomimetic cases did show some differences. For example, while all three boiler energy reductions were 80% ± 10%, the chiller (cooling) reductions in the Education case was 41%, while in the Office and Aged Care cases, the reduction was around 70%. The lower reduction in cooling for the Education case was the nature of the internal loads, with the Education case having a much larger occupancy. The high occupancy of 2 m^2 per person resulted in internal loads being 87% higher in the Education case compared to the Office case. The additional occupancy also required air for occupant ventilation, and necessitating a higher conditioning demand for outside air. The inclusion of a high-performance biomimetic façade could not affect the conditioning requirement for outside air, and this illustrated one of the limitations of the proposed design. It was apparent that the biomimetic façade would be more effective at reducing services energy consumption in building types where envelope heat loads dominated the load profile, rather than occupant loads and outside air. There was a higher proportional reduction in fan energy in the Education (28%) case compared with the Office (15%) and Aged Care (11%) cases. This result followed from the climate zone studies, which suggested that insulation building envelope strategies would have a limit to their effectiveness if internal loads and insulation were not improved as well.

Peak heating and cooling comparison: building types

Figure 13 shows the peak heating and cooling loads for the building type simulations with the biomimetic façade, including reference cases.

Absolute peak heating and cooling was relatively similar for the three building types, although the higher internal loads in the Education case drove a higher cooling demand. The heating demand peaks in the Education and Aged Care simulations were lower than the baseline Office case. The Education case was lower because of a later start time in the assumed schedule (09:30) compared to the office (08:30) and would operate with higher internal loads. The Aged Care case was assumed to operate continuously, and would therefore not need to start up from a cold, unoccupied building (noting again that these were *dynamic* peak loads and not *design* peak loads).

In comparing the effect of the biomimetic façade on the peak loads across the building types, it was observed that the proportional cooling reduction achieved through the

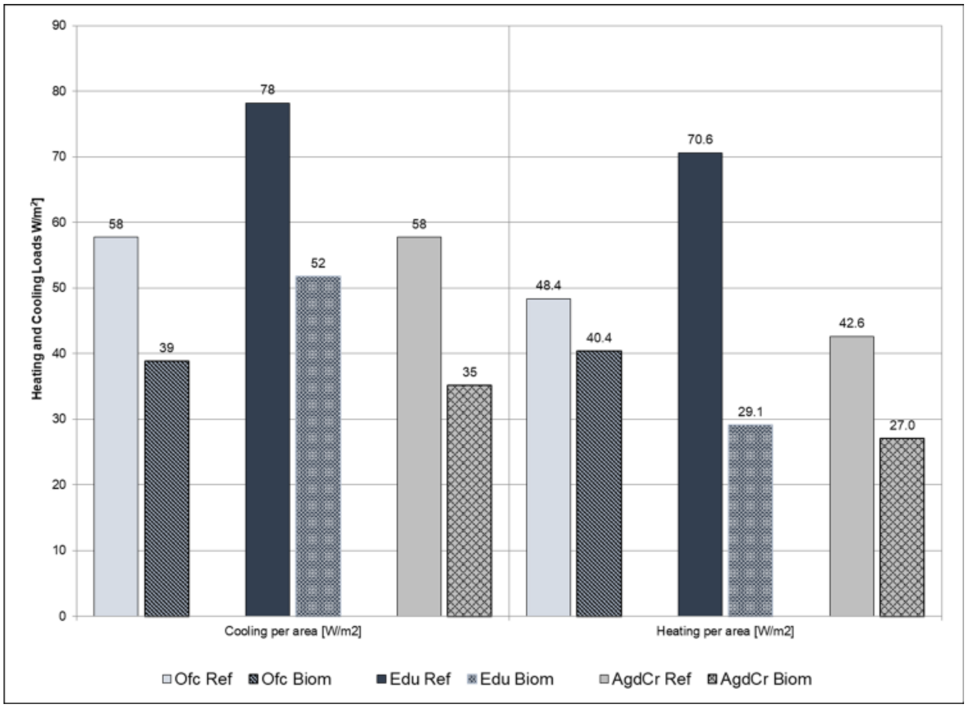


Fig. 13 Peak heating and cooling for different climates—comparison

biomimetic façade was similar for all three cases, with a 35% ± 5% decrease in cooling when compared with the reference case. In heating, there was more of a difference in the building types, with a 17% reduction in offices, 60% reduction in the Education case and 37% reduction in the Aged Care case. The large reduction in the Education case could be attributed to the retention of internal heat from occupants due to an improved external insulation from the fur lining. In the Aged Care case, the better performance of the biomimetic façade was due to the efficiency of the perfusion system to deliver heating via hot water perfusion through the building envelope, which, once reaching the maximum allowable temperature, would have created only small ongoing demand due to losses to the external environment through a well-insulated, fur-lined, external façade. The results for the Education and Aged Care facilities illustrated the effectiveness of the additional insulation provided by the fur layer and the efficient form of space heating achieved through perfusion through the façade. This would be especially applicable climates where heating demand is significant, such as the Cfb climate tested (Melbourne Australia) and in colder climates, such as the Dfb climate (e.g. Stockholm, Sweden).

Comparison with simulation and energy reduction studies

This study was undertaken to simulate the potential effect of biomimetic facades with the aim to decrease energy consumption in buildings of different type in different climate zones. To place the results of the study in context with other research, a review was conducted on other simulation studies where energy-saving initiatives have been proposed for buildings in different climate zones, with an emphasis on innovations for building envelopes or performance improvements in HVAC systems. A summary of comparative studies is indicated in Table 11.

The energy simulation studies noted in Table 11 may be further summarised by climate zone building type and energy reduction. This comparison was completed and compared against an equivalent summarisation of the scenarios tested in the current assessment of biomimetic facades, as shown in Table 12. Note: for additional data points, individual scenario outcomes were separated in each reference paper, where possible.

Table 12 indicates a substantial difference in energy reduction achieved through the biomimetic design compared with alternative energy efficiency initiatives. A statistical comparison of the biomimetic scenarios against the sample of alternative studies using a t test of unequal variances suggests that there is a very low probability (<0.001) that the energy reductions from these two groups are equal, i.e. the greater magnitude achieved by the biomimetic designs may be considered statistically significant. However, it was noted that both samples sizes were relatively small and future work is recommended to extend this comparison.

Table 11 Alternative simulation and energy reduction studies

Study	Location	Climate zone	Building type	Methodology	Building feature or initiative	Result
Webb (2017)	Dandenong, Melbourne, Australia	Cfb (Temperate Oceanic)	Office	Simulated building HVAC upgrade measures compared to measured sub meter data	Pressure reset hardware and controls implemented on building HVAC air handling units	Energy consumption reduced by 22% on annual basis
Zhang and Bannister (2017)	Canberra, Australia	Cfb (Temperate Oceanic)	Office	Validation of a building simulation model against actual energy data from case study office building	Five fabric or HVAC upgrades proposed, from VAV upgrades, evaporative pads, air controls, insulation and start time, supply air temperatures and a combination set of measures	Energy consumption reductions from the reference ranged from 1.6% (outside air controls), through to 33.3% (combined VAV, evaporative pads and outside air controls)
Cho et al. (2019)	Seoul, South Korea	Dwa (Monsoon-influenced hot-summer humid continental climate)	Apartments	Mid-rise apartments in Seoul were tested with four different types of external fabric insulation with ASHRAE standard 90.1 assumptions. Further energy-saving initiatives also tested	Insulation was increased from a reference of 2.572 m2K/W up to 6.8 m2K/W and 8.8 m2K/W	Substantial increase in thermal insulation led to reductions of up to 29% in combined annual heating and cooling energy. Additional building envelope initiatives led to an additional 7% improvement in heating and cooling energy
Kwok et al. (2017)	Hong Kong	Cwa (Monsoon-influenced humid subtropical climate)	Public housing apartments	Four different rental housing configurations were tested with conventional Test Reference Year and Summer Reference Year (near-extreme) weather	Different energy outcomes assessed for different building configurations. Potential energy savings explored by various passive design strategies, including shading and reducing the exposed cooled space	Cross-shaped building appears to be more efficient. 'Harmony' (cross) arrangement used 16% less energy than other building configurations. When a range of passive design features were analysed, specific apartment layout (including outdoor shading, windows and balcony) in a cross configuration achieved ~ 18% energy reduction compared with the baseline. Other initiatives saved less than 10% in energy

Table 11 (continued)

Study	Location	Climate zone	Building type	Methodology	Building feature or initiative	Result
Yigit and Ozorhon (2018)	Istanbul, Turkey	Csa (Hot-summer Mediterranean climate)	Multi-storey residential building	Parametric optimisation of energy consumption via the use of building envelope parameter selection and cost constraints	Genetic algorithm to optimise multi-variable system. Parameters were wall and roof absorptance coefficients, window surface area, wall, roof, window and slab types. Constraints were set as budget costs	Across the four cases tested (with increasing budgets), the maximum energy saving from the lowest cost solution to the highest cost solution was 6.7%
Dahanayake and Chow (2017)	Hong Kong and Wuhan, China	Wuhan: Cfa (Humid subtropical climate) Hong Kong: Cwa (Humid subtropical climate)	Residential flat	Vertical Greenery Systems simulated in EnergyPlus using the module included in the software	Assessment of cooling and heating effects of VGS compared with a bare wall	For a summer day in both Hong Kong and Wuhan, external surface temperatures were very close to air temperatures with VGS (Vertical Greenery Systems) while bare façade temperatures reach 60 °C and above. Energy differences between bare wall and VGS were small. Overall, annual energy consumption was reduced by 0.3% in Wuhan and 3% in Hong Kong. Study indicated a greater effect for VGS at reducing energy consumption occurred in summer compared with annual results

Table 11 (continued)

Study	Location	Climate zone	Building type	Methodology	Building feature or initiative	Result
Baniassadi et al. (2018)	13 locations in the United States	Range of A through D climate classes	Single-storey supermarket	Simulation of novel hybrid roofing system that includes beneficial characteristics of both green roofs and high albedo roofs	Bare roof compared with a green roof and innovative hybrid roof with combined effects of green roof and high albedo	The displays results using Operational Performance Factor, which describes the relative improvement of the hybrid roof. The results suggest that a hybrid roof would outperform white or green roofs by a factor of 50%-100%. However, this is given in comparative terms between two initiatives and not the actual energy consumption

Limitations and further work

The basis preceding work showed the potential for biomimetic building facades as a means to reduce operational energy consumption and maintain thermal comfort for several climate zones and building types. This result was based on digital designs and modelling, which were subject to assumptions and limitations.

Building on this work, the biomimetic model could be further developed. There are opportunities to develop the model further to include additional effects and increase the accuracy of the Pennes bioheat equation, as in Cena and Monteith (1975a, b), He et al. (2011), Charny (1992), Weinbaum et al. (1997) and Jiji (2009). Furthermore, the modelling of animal tissue could be varied to account for differences in tissue physiology that are apparent in different species. Potential model frameworks include Parry (1949), Ackman et al. (1975), Lockyer et al. (1984, 1985); Schmidt-Nielsen (1997) and Liwanag (2008).

Furthermore, there are many examples of natural adaption to acute and seasonal weather variation. Such dynamic response represents a potentially powerful direction in which to further develop the biomimetic facades. There are also opportunities to adapt and optimise fur and perfusion properties to suit specific locations. Heating optimisation would benefit the results obtained for the Dfb climate, while in tropical climates, management of air moisture content is important. Preliminary heating optimisation preliminary heating optimisation study was conducted for a furlined façade during winter heating in Melbourne, Australia (Webb et al. 2011). Addtionally, nature-inspired initiatives to remove moisture from the air could be investigated, e.g. trees that remove fog from the air (Goldsmith et al. 2013) and species of orchid that absorb moisture from a humid atmosphere (Zotz and Winkler 2013).

As highlighted in the results, it was apparent that the performance improvement achieved by the biomimetic façade was dependent upon the load balance. When building envelope loads were dominant, the greatest energy reductions were achieved. However, in situations with lower impact of building envelope heat loads, smaller energy reductions were achieved by the biomimetic facades. Additional investigation may be conducted to identify nature-inspired characteristics to improve latent heat management and ventilation heat exchange. For example, respiratory heat exchange in vertebrates Schmidt-Nielsen et al. (1970), counter current heat exchange in elephant seals (Huntley et al. 1984) and brain heat flow management in Thomson's gazelles (Taylor and Lyman 1972).

The comparison between biomimetic facades and alternative energy efficiency initiatives indicated that biomimetic designs could achieve a significantly greater energy

Table 12 Alternative simulation and energy reduction studies—results summary

Study	Building type	Climate	Energy consumption reduction (%)
Alternative energy simulation studies			
Webb (2017)	Office	Cfb	− 22
Zhang and Bannister (2017)	Office	Cfb	− 1.60
Zhang and Bannister (2017)	Office	Cfb	− 33.30
Cho et al. (2019)	Apartments	Dwa	− 29
Cho et al. (2019)	Apartments	Dwa	− 36
Kwok et al. (2017)	Apartments	Cwa	− 18
Kwok et al. (2017)	Apartments	Cwa	− 16
Yigit and Ozorhon (2018)	Multi-residential	Csa	− 6.70
Dahanayake and Chow (2017)	Apartments	Cfa	− 3
Dahanayake and Chow (2017)	Apartments	Cwa	− 3
		Mean for alternative studies	− 16.86
Scenarios tested in current study			
Climate zone biomimetic	Office	Dfb	− 55.1
Climate zone biomimetic	Office	Bwh	− 49.4
Climate zone biomimetic	Office	Aw	− 55.4
Building type biomimetic	Office	Cfb	− 46.2
Building type biomimetic	Educational	Cfb	− 42.6
Building type biomimetic	Aged care	Cfb	− 67.1
		Mean for scenarios tested in current study	− 52.6

reduction. However, the sample size for alterative studies was small, and not all climate zones or building types were included. Still, the biomimetic scenarios showed similar performance results regardless of the building or climate category.

Furthermore, this study relied on digital modelling and simulation. TRNSYS software is based on fundamental numerical modelling techniques and has been a key component of testing and development of the validation method for building simulation software, ASHRAE Standard 140-2017 Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs (ASHRAE 140-2017 2017). It has been shown to be an effective simulation tool for built environment studies, with widespread use in numerous publications (*Papers and Validation—Journals with References to TRNSYS*). However, digital modelling is subject to assumptions and simplifications. Future efforts will focus on fabrication of physical prototypes for validation testing to test the conclusions drawn in this study.

Materials and fabrication form an important pillar of future work. Industry 4.0 (Stock and Seliger 2016) provides opportunities for waste minimisation, recycling and dematerialisation (Brownell 2008). However, advanced manufacturing—though digital fabrication and rapid prototyping—offers capability to deliver complexity and precision required to manufacture the proposed biomimetic facades. New fibres such as Vectran (Vectran 2010), a liquid crystal polymer, demonstrate the possible properties for durable fibrous materials required for the biomimetic façade. New 3D printing technology (Ngo et al. 2018) can provide precision manufacturing necessary to fabricate the façade. This includes the precision required to create the structures necessary for fur fibres and the perfusion materials (Zhang et al. 2017). Additive manufacturing has recently been tested on a full-scale façade module (Mungenast 2021) and provides opportunities to improve sustainability (Ford and Despeisse 2016).

This study focussed on the performance capability potential for a biomimetic building skin. Further work is necessary to understand the economic feasibility of such building initiatives. While, as noted in the Introduction, there have been studies that have investigated applications of biomimicry to architecture and building skins, little emphasis has been placed on the economic feasibility and constructability. Exploration architecture have proposed a high-performance office building employing a number of biomimetic features; however, the project remains at a design stage (The Biomimetic Office Building 2021). Chayaamor-Heil and Hannachi-Belkadi (2017) proposed a Bayesian Network as a method to organise complex decisions involved in applying biomimicry to building design; however, they focussed technical requirements rather than economic considerations. Broader studies have suggested an increasing development and application of biomimetic innovation in multiple industrial sectors; however, there is a gap in research on specific economic feasibility of specific biomimetic initiatives for architecture. Smith et al. (2015) identify biomimicry as a burgeoning innovation opportunity, and identifies research, development and production in nine industrial sectors, noting that developments in carbon, water, materials, energy conversion and storage, fluid dynamics, data and computing and systems analysis all have potential application to buildings. However, these technologies, especially those currently in development or available in the market are mostly component and materials-based. The study does not investigate these technologies in the context of a construction project. In the same study, the authors site research by Fermanian Business and Economic Institute estimated that bioinspiration could account for $425 billion in US GDP and 2 million jobs. A large proportion of benefit is estimated for the building sector (approximately $70 million) however feasibility of individual technologies is not specified.

Other researchers have investigated the funding, financing and policy incentives for sustainable, higher-performing buildings. For example, Diwekar (2015) suggests a more holistic perspective is required for engineering sustainability. Chen and Hong (2015) indicate that, from a Chinese perspective, subsidies do play a role in incentivising green buildings, and that improving information flow will contribute to more green building, while Staniškis and Stasiškienë (2003) presented a model for facilitating cleaner production incentives in developing countries. Finally, Muo and Azeez (2019) took a broad view of green entrepreneurship and the factors influencing businesses to maintain "business-as-usual practices", concluding that while benefits of green entrepreneurship are enormous and it has a role in creating a sustainable green economy, there are several concerns preventing more widespread adoption, such as inclusiveness and greenwashing. The authors suggest that change management should be a future focus for green entrepreneurship. The development of high-performance biomimetic façades must contend with these societal and economic conditions to be a viable option in future construction. Opportunities should be sought for governmental green financing and newer investment pathways.

Conclusions

Society must rapidly decrease carbon emissions to mitigate dangerous climate change. Since buildings consume a significant proportion of energy, drawn from carbon-intensive electricity grids, improving energy efficiency is a necessary step. With the development of active façade technology, smart buildings and Industry 4.0, applications of biomimicry can achieve further energy and carbon reductions. Biomimicry—"innovation inspired by nature"—has been adopted in multiple technological and engineering fields as a framework for innovation and improvement. This study tested the hypothesis that the animal fur-perfusion façade design would reduce building services energy consumption in different building types and varying climates at least as much as shown for offices in a temperate climate. Modelling demonstrated the hypothesis to be confirmed. Results showed the biomimetic façade had strong potential to reduce operational energy consumption in the order of 50% for all different climate zones and in all building types. Furthermore, with one exception (heating in Dfc climate zone), the biomimetic façade showed a decrease in dynamic peak heating and cooling demand, again by up to 50%. The physical characteristics of the fur lining to provide extra insulation and a barrier to incoming solar radiation, in combination with the water-based perfusion inside the façade, were effective in improving the building envelope energy efficiency.

Energy efficiency and peak heating and cooling loads varied across the climate zones and building types. In each alternative climate zone, the percentage energy reduction achieved over a reference baseline was greater than in the original study for a Cfb climate. The greatest percentage decrease was achieved in the tropical Aw climate (3112 kWh, or 55.4%). When testing peak cooling, the tropical Aw climate also had the greatest reduction of 51%. In all of the climate zones, the magnitude of the energy decrease was greater than that for the baseline, temperate, Cfb, climate zone.

Across building types, the Aged Care simulation showed the greatest potential for energy savings, with a 67.1% reduction over the reference, the Education type indicated a 42.6% reduction compared with the original Office study at 46.2%. As for climate zones, results substantiated the study hypothesis. There was a significant improvement in heating efficiency in all three building types, owing to the insulative effect of the building fur and efficient water-based heat transfer from perfusion.

The proposed fur-perfusion façade was compared to other energy simulation studies focussed on building envelope energy efficiency or upgrades. This comparison indicated that the fur-perfusion facade performed statistically better in energy reduction than alternatives; however, the sample size was limited.

These results confirmed the study hypothesis that the biomimetic façade design would improve energy efficiency and reduce peak demand in different climate zones and building types. Both findings were significant in both environmental and economic terms. Building operational energy savings equate to lower supply from carbon-intensive electricity grids and cost savings for building owners. Reductions in peak demand reduce pressure on peak capacity on electrical infrastructure, which can lead to carbon intensification of electricity supply and more greenhouse gas emissions.

Peak demand reduction also reduces peak demand tariffs for owners, delivering more significant cost savings.

Using this case study, the research has demonstrated the potential for biomimetic facades to have a substantial impact on the performance of building envelopes to decrease energy consumption and peak demand across multiple climate zones and building types, leading to reductions in carbon emissions and lower demand on electrical infrastructure. Additionally, the research demonstrated viable mathematical modelling and building simulation methods that could be applied for alternative biomimetic initiatives for building facades. Further work to investigate the production and manufacture, physical validation and economic feasibility will strengthen the case for application of the fur-perfusion facades to decrease the energy and carbon footprint of buildings, while contributing economic advantages and sustainability of building materials.

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Data availability Data on results is available upon request.

Code availability Software code is not openly available; however, the author is willing to discuss the modelling protocols in detail with interested parties.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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