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Bio-inspired cooling technologies and the applications in buildings

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ABSTRACT

In response to the growing demand for indoor environmental quality (IEQ) and energy efficiency, abundant innovative bio-inspired cooling technologies have been proposed and their applications in buildings have been greatly demonstrated in the previous decades to enhance the benefits of building occupants. IEQ is associated with human health and productivity but maintaining good IEQ requires continuous air-conditioning resulting in a high energy consumption, especially space cooling. Bio-inspired cooling technologies focus on the fundamental mechanisms of heat transfer used by animals or plants which are considered as the keys to create a harmony between buildings and the nature, whereby IEQ can be enhanced while achieving energy efficiency. This review provides a comprehensive summary on the current bio-inspired cooling technologies, including the concepts in the research stage and the well-developed products applied in buildings, and discusses some promising designs that have the most potential for future applications. This paper is structured according to building elements, in which technologies regarding HVAC system, building materials, opaque building envelope and transparent building envelope are reviewed. The heat transfer mechanisms behind each technology including conduction, convection, evaporation or phase change and radiation are discussed. Yet successful green buildings involve a smart thermal management system for which a section is dedicated to discussing various approaches in design optimization. In the last section, a case study simulation of implementation of bio-inspired cooling technologies in a house and its energy efficient performance are analyzed. The authors attempt to motivate the future research and development in energy efficient buildings.

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1. Introduction

Archaeological and historical evidence indicates that buildings existed since the Iron Age. Great Pyramid of Giza was constructed over 3800 years ago. In ancient time, the purpose of houses was to protect mankind from any kind of danger like extreme weather conditions, animal attacks, or human enemies. As there were no active air-conditioning units in the past, those houses were designed and built adopting their surrounding environment, thereby passively providing occupants enough fresh air, sunlight, warmth, and other necessities for survival. Following the timeline of civilization, those houses were no longer just shelters but integrated with many functionalities powered by natural resources to provide a more favorable environment than the outdoor, giving a higher standard of living and improving human's health, comfort, and productivity. Due to the development of heating, ventilation, and air conditioning (HVAC) a century ago, the architecture of buildings can be less limited by the natural environment, but at the cost of dramatic increase of energy usage. Modern buildings, especially in developed countries, constitute a significant portion (around 20–40%) of the total social energy consumption. For example, in 2018, about 40% of total energy in U.S. was consumed in residential and commercial buildings [1]. Both governments and scientists have identified the imperative need for energy saving in buildings. Several regulations and labeling schemes have been set up in national and international level to promote energy efficiency in green buildings. These regulations and labeling schemes focus on various life cycle stages of buildings and levels of building components. For example, in Europe, a concept called nearly Zero Energy Building (nZEB) has been implemented by the European Union and other agreeing countries to have all buildings in the region under nZEB standards by 2020 [2], which means all the buildings have to use green resources with very high energy performance. Regulations have been enforced so that the buildings, especially the new public buildings, should have nearly zero or very low energy consumption, and the amount should be mainly covered by on-site or nearby renewable sources. Other than the regulations, labeling schemes have been established in the globe. Most of them are voluntary labeling programs, but many state and local governments rely on some of them. The world green building council has networked around 70 local councils to initiate green buildings around the world, so that a number of localized green building certification systems for environmental labeling have been set up, e.g. Leadership in Energy and Environmental Design (LEED) from U.S., Building Research Establishment Environmental Assessment Method (BREEAM) from U.K. and Building Environmental Assessment Method (BEAM) Plus from Hong Kong. LEED evaluates a building through its design, constructions, operations, and performance to make sure not only the occupant but also the community can benefit from the sustainable building. Similar to LEED, BREEAM certificates are served for master planning projects, infrastructures and buildings, which consider their sustainable performance throughout the environmental lifecycle. The Green Building Counsels in Hong Kong has launched BEAM Plus to promote and help the industry to adopt green building. BEAM Plus offers a comprehensive set of performance criteria for a wide range of sustainability issues relating to the planning, design, construction, commissioning, management, operation and maintenance of a building. Other than the environmental labeling, for the use of green products and systems in buildings, there are various labeling and certification throughout the world. Energy Star is a popular labeling system established in the United States, of which the considering criteria are how much energy the appliance uses, the strength among similar products, as well as the annual costs. The product lists of Energy Star include audiovisual equipment, office equipment, heating and cooling equipment, etc. Energy Star belongs to the group of Ecolabels and it is voluntary. Another voluntary labeling system is EU Ecolabel in Europe, which takes the environmental impact on the whole product life cycle into consideration. Hong Kong has recently launched the CIC Green Product Certification, which is a building and construction products/materials certification scheme serving the Hong Kong construction industry. The certified products ranged from a title to a chiller.

Adopting energy efficient strategies in buildings, especially in space cooling, is a promising direction. Among different kinds of energy consumptions in building, space cooling or space conditioning takes up a significant portion. Surveys show that approximately 31% of the end use of building energy in HK [3] and 50% in worldwide [4] is consumed in space conditioning. There are various strategies for saving energy in space conditioning, and they can be broadly categorized as active or passive strategies [5]. Active strategies regard as the energy efficient improvements of the HVAC systems which is a popular research topic. Effective heat exchanger and advanced working fluid are some hot research topics. Passive strategies improve the building envelope elements in order to reduce the energy or heat loss. A building envelope element refers to roof, wall, windows, façade, etc. which separates the indoor and outdoor environments of a building, through which a huge amount of heat fluxes is transferred due to their large surface area. Innovative building materials with designed and functional thermal mass and thermal insulation have been studied. Other than the building materials, energy usage can also be reduced significantly by a proper architectural design. For example, a large portion of the heat transmission comes from solar energy which occurs in daytimes with time-dependent orientation. Thus, a smart design to block or shade summer sun while to permit winter sun in suitable time can also be regarded as a passive strategy [6]. This example demonstrated the importance of the relationship between buildings and nature. Ensuring harmony between buildings and the natural environment is a potential direction for a successful strategy.

Nature has already inspired many scientists and engineers to solve various technical problems. By searching keywords: "bio-inspired", "nature-inspired", "biomimicry", "biomimetic" or "bio-mimic" in Scopus, it is found that the number of research papers (i.e. journal articles, conference papers and meeting abstracts) is increased from 202 in 1998, 1659 in 2008, to 4141 in 2018. The statistics from Web of Science are similar (i.e. 206 in 1998, 1081 in 2008 and 4138 in 2018). It should be noted that the keywords for searching are not exhaustive, but the quadratic increase of the number of research papers per year shows that researchers believed that bio-inspiration is a promising approach in tackling engineering problems. The solution given from nature is more likely to be in harmony with the natural environment, which is important for developing energy efficient building technologies. Nature has inspired a lot of research works in different fields of technologies. For example, nature-inspired or bio-inspired technologies have already drawn worldwide attention in construction engineering [7]. In this review paper, we are interested in all bio-inspirations that can achieve cooling purpose and applied in buildings. Moreover, the bio-inspirations to be considered are not only to imitate plants and animals shapes and forms, but to find strategies, logic and methods in design that are analogous to nature's process. Under this definition, different classification methods can be used to discuss the application of bio-inspired cooling technologies to buildings. One approach is to classify them in different heat transfer mechanism: conduction, convection, evaporation/phase change and radiation. Another approach is to classify the technologies in different application scales: building elements, architectures, and systems [8]. Building elements include components in HVAC system, building materials, opaque building envelope (e.g. roof, wall, etc.) and transparent building envelope (e.g. window). Most of the bio-inspired techniques aim at mimicking the nature and to achieve the cooling or thermal management function in particular building elements. For example, recently, radiative materials for roof/wall by the principle of passive radiative cooling observed from Saharan silver ants was proposed. Another example is an evaporative heat exchanger inspired by animal sweat glands system that enhances the cooling effect by evaporation [9]. Fig. 1 illustrates how different bio-inspired building elements integrate into a house to achieve energy efficiency. The application in scale of architectures means different building elements form together in architectural scale to achieve a function mimicking the nature. Termite mound is an example in this scale that makes good use of the natural convection. In system scale, both passive and active strategies, and different techniques work together under a bio-inspired thermal management system. For instance, some birds dissipate heat by both gular flutter (i.e. panting and causing airflow induced vibration in the gular region) and vasodilation (i.e. expansion of blood vessel in the gular region). Their brains control these two mechanisms simultaneously to achieve the optimal thermoregulation. Similarly, thermal management systems are needed to monitor the systems of multiple strategies. Table 1 lists a number of bio-inspired technologies in real application or in research stage applied in buildings, together with the classifications in heat transfer mechanism and in application scale for each technology.

Bio-inspired cooling technologies applied in buildings are reviewed in this paper. The objectives are to review the current technologies including both in real application and in research stage, to discuss its feasibility, and to identify the potential trend of the field. We aim at answering the following questions: what phenomena have been observed in the nature that inspired the scientists and engineers? How is the phenomena related to heat transfer? What technologies have been developed by this observation? The paper will be organized in terms of building elements and application scale. Firstly, bio-inspired technologies to improve HVAC systems will be discussed followed by the review of building element technologies. Opaque and transparent building elements will be introduced one-by-one. Then, a bio-inspired natural convection case in architectural scale will be discussed and bio-inspired thermal management techniques will be reviewed. Understanding the heat flux mechanism behind of each bio-phenomenon would be helpful to achieve our objectives. Therefore, the heat transfer mechanisms will also be explained. Finally, a case study simulation will be conducted to analyze the potential of using bio-inspired technologies in buildings to improve energy efficiency.

2. Bio-inspired technologies to improve HVAC system

To improve the heat transfer of an existing HVAC system in order to enhance its efficiency, there are two major approaches: increasing the convective heat transfer and enhancement by phase change or evaporation. Convection, the heat transfer process

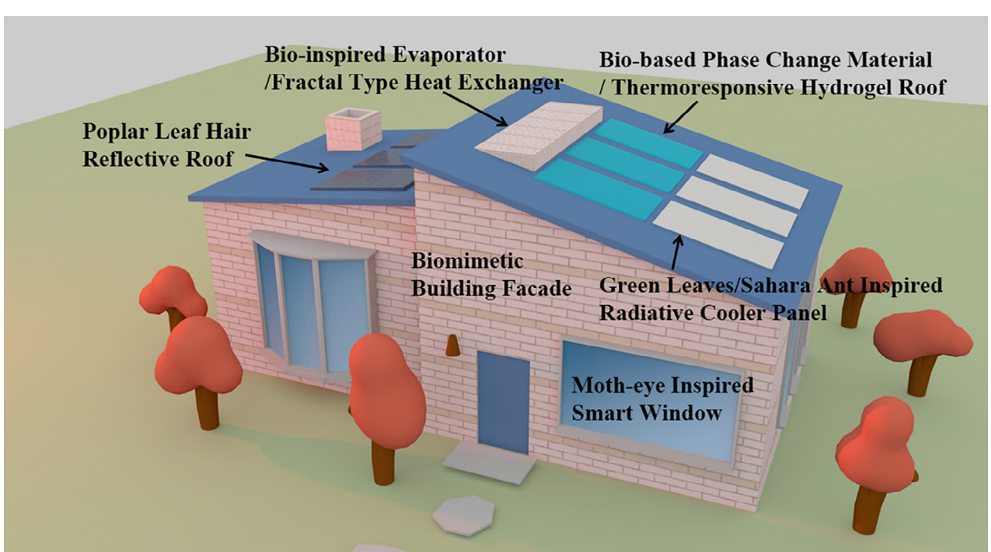

Fig. 1. Different bio-inspired building elements integrate into a house to achieve energy efficiency.

Table 1
List of bio-inspired cooling technologies applied in buildings.

Inspired by	Application inspired	Application Scale	Building elements involved	Heat transfer mechanism	References
Leaf vein structure, lung and blood vein structure	Fractal channel, fractal tube-in-tube heat exchanger	building elements	Heat exchanger, heat sink	Convection	[9-17]
Elephant fluttering ear and bird's gular flutter	Fan integrated heat exchanger, heat sink or façade cooling enhancement by flutter (potential)	building elements	Heat exchanger, heat sink	Convection	[10,18-23]
Sweat glands system of mammals	Evaporative condensers in heat exchanger technology	building elements	heat exchanger, condenser	Evaporation	[9,24-26]
Catus and beetle shell	Two-phase micro-pillar heat sink	building elements	Heat sink	Evaporation	[27-29]
Hairs of polar bears	Hollow fiber structure with low thermal conductivity, potential for building materials	building elements	Building material	Conduction	[30-32]
Penguins' pelts	Biomimetic building façades	building elements	Building façade material	Conduction	[33-35]
Beehives or wasp nests	Planar hexagonal comb structure for building materials	building elements	Building material	Conduction	[36-44]
Sweating skin of mammals	Thermoresponsive hydrogel as roof coating, artificial skin material,	building elements	Roof	Evaporation	[45-49]
Phase change properties of blubbers in northern mammals and dolphin blubbers	Phase change material used in roofs, ceilings, glass windows, walls and floors, building concretes, building furniture, equipment and systems. Bio-based PCM, less flammable and safer for building applications	building elements	Roofs, ceilings, glass windows, walls, floors	Phase change	[5,50-68]
Poplar leaf hair	Reflective roof that increases the heat reflectivity	building elements	Roof	Radiation	[69-72]
Mist on a surface, green leaves, natural wood, Sahara Ant	Passive radiative cooler, Daytime radiative cooling	building elements	Roof, wall	Radiation	[73-83]
Moth-eye antireflection surfaces	High-performance thermochromic smart window to block solar heat but allow sunlight transmission	building elements	Window	Radiation	[84-89]
Termite mounds, bee nest	Building façade facilitating natural convection	architectures	–	Convection	[38,90-94]
Neural systems in biological brains	Residential thermal comfort, energy savings, HVAC and thermal control by Artificial neural network	Systems	–	All	[8,95-111]
Evolution through the process of natural selection	Building design optimization by genetic algorithms	Systems	–	All	[112-128]

through the movement of fluid driven by temperature gradient, has been largely adopted by natural species to regulate their body temperature. Another body temperature regulating mechanism is phase change, which is a process that matters change from one state to another, i.e. from solid to liquid, liquid to vapor, solid to vapor directly, and vice versa. The most familiar phase change based cooling strategy should be sweating. When the body temperature rises, animals sweat, thereby dissipating heat through the evaporation of the droplets. Indeed, nature creatures are good at using phase change properties to survive in extreme environments or climates. These two energy efficient mechanisms are the major inspirations behind some current cooling and ventilation systems in buildings.

2.1. Heat exchanger enhancement by fractal blood networks

Elephants have a vast and fine blood vessel networks embedded inside their large pinnae to facilitate heat dissipation [10]. The fractal geometry of their blood vessel is commonly found in the respiratory and vascular systems of many animals and plants, and widely employed to facilitate convective heat transfer and mass exchange [9]. The concept has been employed in some high-performance heat exchanger designs to minimize energy consumption. Many experimental and theoretical research studies have been done on fractal heat sinks. Among them, most have concluded that fractal heat sinks have a higher overall heat transfer rate and lower pressure drop than parallel and serpentine channel heat sinks [11-17].

2.2. Heat sink enhancement inspired by birds' gular fluttering

Under heat challenges, birds, e.g. cormorants, pelicans, quail, open their bill widely and pant like dogs. However, this active motion consumes a large amount of energy, and panting alone sometimes cannot prevent them from overheating [18]. When it happens, birds flutter their gular region rapidly supplementing to panting [19,20]. This phenomenon can also be observed in other animals, e.g. elephants' flapping ears and bats' fanning wings. The cooling principle behind is forced convection. Animals boost the convective heat transfer and the evaporative heat losses from the mud or dirt of elephant' body, sweat of bats, or dog's and bird's respiratory and digestive tracts by increasing the rate and amplitude of their breathing [10,21]. During gular flutter, heat is transferred from the blood vessels to the skin surface and through the moist membranes into the rapid moving air, and finally the airflow brings the heat from the birds' mouth to the ambient. The overall body temperature of the bird is greatly reduced through the increase of blood flow and the cooling of the fluttering gular skin [22]. In some birds, the amplitudes of gular flutter increase with ambient temperature, but the frequencies are independent of the heat stress. It is suggested that these frequencies match with the natural frequencies of the gular structure [18,22], thus the extra metabolic cost is little in the process. Many studies suggested that the rate of heat transfer can be enhanced by the fluttering mechanism and it is due to the induced vortices on the thermal boundary layer developed on the heated surfaces [23]. This is potential to be developed into a novel technologies for heat exchanger.

2.3. Evaporative heat exchanger inspired by sweating skin of mammal

To meet the energy requirement of green buildings, scientists have also started to search for inspiration from those phase-change related natural phenomena. Phase transitions involve a large amount of latent heat release or heat absorption whereby they have a high potential to solve or ease the building thermal energy consumption problems. The energy consumption for cooling in buildings in hot summer is huge and the design of an effective HVAC system or heat exchanger is critical to decrease the total building energy consumption. Besides, it would be desirable if the thermal energy in over-heating conditions can be stored for solving the building heating problems in the cold area or winters. Nature provides us some vivid solutions and here are some biomimicry examples of phase-change related applications in energy saving for building applications.

People sweat when the inner body temperature rises. Sweating absorbs the excess heat from the body and dissipates it to the surrounding environment, thereby cooling down the body. Inspired by this phenomenon, some evaporative heat condensers and exchangers have been developed [24]. Application of evaporative condensers in heat exchanger technology [9,25] was reported to reduce up to 58% of the power consumption, compared with an air-cooled condenser [26].

2.4. Two-phase (liquid–vapor) micro-pillar heat sink inspired by cactus and beetle

Another bio-inspiration is about water collection by tip of cactus spine or peaks of beetle bump. Opuntia microdasys [27] and desert beetle [28] can survive in extremely dry environments because the staggered wettability surface of cactus and beetle shell help collecting water from the arid surroundings. The tip of the cactus spine and the peaks of the beetle bump are hydrophobic, while the sides and the base of the cactus spine and the bumps are hydrophilic. This structure is beneficial for collecting small fog water droplets, which are easily lost in the desert environment. Inspired by this, Ma et al. [29] proposed a two-phase (liquid–vapor) micro-pillar heat sink with hydrophobic pillar tops and a hydrophilic base to separate vapor and liquid paths, and found this bio-inspired heat sink has higher nucleate boiling heat transfer and higher critical heat flux. Their results provide a possibility of developing a high-performance heat sink in HVAC system to decrease the cooling energy consumption in buildings.

3. Bio-inspired building envelope – Opaque and transparent building elements

Building elements for building envelope are divided into opaque and transparent building elements. Examples are interior construction materials, wall, roof, exterior for façade, windows, etc. The related bio-inspired technologies basically, involve either these three major heat transfer mechanisms: conduction, phase change including evaporation or radiation.

3.1. Building material with low conductivity by air trapping similar to polar bear's fur

Conduction occurs when two bodies at different temperature are in touch, in which heat flows from the higher-temperature body to the lower-temperature one. This happens not only between solid objects, but also between solids and their surrounding fluid. Thus, animals may loss a significant amount of heat to the air through conduction leading to risks of survival, especially when the weather is extremely cold like in the poles. Human beings put on clothes to keep warm, while wild animals have evolved thermal insulation methods to keep themselves alive. The most known thermal barrier is probably fur and feathers of some animals like mammals and birds, which reduce thermal conductivity by trapping a layer of air covering the animal body. Scientists and engineers were inspired by these phenomena and employed the mechanisms of natural conductive heat transfer suppression on building technology, whereby buildings could be insulated from their local environment including climate. To transform bio-strategies into technologies, research studies aim to develop building materials and construction methods that are analogy to the elements forming the skin of animals and their structures.

Polar bears can maintain their body temperature at about 35 °C even in extreme cold environments, where the winter temperature reaches −20 °C. The insulating power comes from the thick layer of fur on their skins that traps a lot of air to provide a thermal barrier. Besides, the water resistant feature of their hair also prevents water drops from staying on and gaining heat from the skin of polar bears. The excellent thermal insulation has attracted attentions from the research field of designing building material with enhanced thermal insulated property [30]. With reference to the hollow structure of the non-wettable hair of polar bears, Zhan et al. [31] has successfully developed and fabricated carbon nanotube aerogel with hollow fiber structure, which has low thermal conductivity ($\sim$0.023 $W\,m^{-1}\,K^{-1}$) as well as excellent elastic and fatigue resistant property, showing a high potential in energy efficient buildings application [32]. In general, the development tends to investigate the thermal properties of porous and tubular structues, which are expected to have a high level of insulation due to the air filled inside the sturctures.

3.2. Building façade material using unique hierarchy structure of Penguins' pelt to trap air

Like polar bears, penguins also live under extreme cold conditions. However, they, as birds, don't have fur to keep them warm. What plays a major role in keeping penguins from the coldness is their pelts. Contrasting from polar bear hair's simple structure, the penguin feather's structure consists of: 1. rachis, which is the main supporting stem of the structure; 2. ramus, barb and barbules, which are branches from the main stems; 3. cilia, which are little hooks on the branches; and 4. after-feather, which are the softer parts of the feather structure. Its unique hierarchy structure in different scales allows the feathers to align in layers to maximize the air trapped inside, as well as the ability of the after-feather to provide conduction insulation. The average overall thermal conductivity of the thick skin and feathers can reach as low as 1.35 $W\,m^{-2}\,K^{-1}$ [33], by which penguins can survive up to 120 days without food supply when they are incubating eggs [34]. Aslam conducted a computer simulation with Design Builder to investigate the possibility of employing the penguin pelt design on building façades, and demonstrated that the biomimetic façade has a lower U-value than the traditional double wall system [35].

3.3. Minimizing building material usage by conductive thermal management as in beehives

Besides the surface features on animals' skin, smart thermoregulation approaches can also be found in hives. Temperature inside the breeding chambers in beehives and wasp nests must be controlled precisely to ensure the health of the newborns [36,37]. The nest architecture is associated with temperature regulation, which has drawn much attention from scientists and researchers to study the correlation [38]. Using the least amount of material, bees construct their honeycomb structure with a plenty of stationary and millimeter scale air spaces to achieve excellent insulation from thermal conduction whereby the hives are less influenced by their outside conditions. The ends of the breeding chambers have adjustable valves. By actively opening and closing these valves and by altering their materials and thickness, the temperature inside the chamber can be continuously maintained at desired values. Because of the excellent thermal insulating properties, such planar hexagonal comb structure has been tested and widely utilized in building material construction [39,40]. Putting insulating materials in hexagonal cavities for building applications can minimize the material usage. Walls, panels and roofs with comb array cladding or embedment have a high potential for future building applications regarding thermal management. Not only can they offer better structural integrity compared to traditional design, but also provide advanced conductive insulation [41-44].

3.4. Building roof as a sweating skin

Another bio-inspiration is the evaporation of mammal's perspiration. The concept of 'sweating skin for building cooling' have been developed [45-49]. Rotzetter et al. [48] synthesized a special thermoresponsive hydrogel (PNIPAM) which can store up to 90 wt % in its swollen state. When it is heated to roughly 32 °C, the gel transits from a wet state to a dry state, and releases water, during which a large amount of the building heat is taken away. They compared the heat transfer effects between two small-scale model houses, an uncoated house and a house coated with the hydrogel. Their results indicated that the model house with roofs coated with these heat-sensitive hydrogels can reach up to 20 °C cooler by comparing with the uncoated model house when exposed to simulated tropical midday sun. It is estimated that this is equivalent to saving 220 kWh of energy per year for a single house.

3.5. Building wallboard and floor using phase change materials inspired by blubber of dolphin

For better energy saving, it is desirable if we can decrease the heat loss through the building envelops in winter or at night, and store the excessive heat in hot summer or daytime which may be used to compensate the heating energy consumption in winter or at night, under the premise of keeping the indoor environment stable and in a comfortable temperature [50]. This thermal consistency property has been found in human beings and a lot of northern mammals. For normal mammals, their fatty tissue plays a role as thermal insulators, but it is also found that phase change properties of the blubbers in the outer layer of the northern mammals can also be applied to store or release heat [51,52]. In particular, it is noted that the deep blubber of the Atlantic bottlenose dolphin has significantly higher heat flux than the superficial surface. Considering the fatty acid composition in the blubber, it is highly suggested that the dolphin blubber can absorb heat as a phase change material [53]. Currently, using phase change material (PCM) to cool building or store building heat is a hot and promising approach. PCM can efficiently absorb the thermal energy in the surrounding environment and store the energy through phase transformation, and release the stored thermal energy through vice versa process [54], keeping the temperature in a relatively steady range. There are many applications of using PCM in buildings [55-57]. For example, Schossig et al. [58] integrated some micro-encapsulated PCMs into plaster and found that the room with PCM plasters could be 4 °C cooler when the indoor temperature was over the melting range. Lv et al. [59] incorporated the building wallboards with PCM and found that the energy cost of HVAC system can be significantly decreased. When the indoor temperature exceeds 18.49 °C, the PCM in wallboards began to melt and absorbed the heat in 39.12 kJ/kg till the temperature at 24.26 °C, which provided a 'cooling' storage for the building and save the electricity cost of air conditioning. The stored latent heat can be released when the room temperature is lower than 18.59 °C, which can greatly decrease the heat energy cost. Besides, the demonstration building with ultra-low energy consumption in Tsinghua University (China, Beijing) applied phase change floor through inserting the PCM with phase transition temperature at 20–22 °C into the building floor [60]. The phase change floor can store the radiation heat that introduced by the glass walls and windows in the winter daytime and release the heat to the indoor environment through reverse phase change process in cold winter night, resulting that the temperature fluctuation indoors would not exceed 6 °C. Another general application of PCM in buildings is the PCM-based concrete [60-65] and it is reported by Figueiredo et al. [65] that the concrete with PCM can slightly reduce the indoor temperature fluctuations. Although PCM application is very popular in building elements, there exists a widely concerned safety problem. Usually, traditional PCMs are flammable and thus hinder their application in building, while the bio-based PCMs are less flammable and safer to use [5,66]. Lipid derived PCMs prepared from fatty acids have a higher heat capacity and a higher desirable phase change temperature [67,68], which provide a possible trend for future PCM development for high thermal energy storage in buildings.

3.6. A highly reflective roof coating similar to the structure of leaf hair

Solar spectrum consists mainly, 44.7% of visible radiation (380 ~ 780 nm), 6.6% of ultraviolet radiation (<380 nm) and 48.7% of infrared radiation (>780 nm). When an object absorbs light waves, the energy carried by the light waves is converted into heat energy if no photovoltaic effect exists. Therefore, buildings are forced to gain excess heat during hot summer days through the absorption of solar energy by building envelopes, including walls, windows and roofs. For example, approximately one-third of heat gain comes from the roof of the building [69]. To prevent undesirable heat gain through solar absorption, building envelopes need to be designed in order to control the transmitted sunlight.

Studies estimate that about 60% of urban areas are covered by roofs and pavements, and the percentage continues to increase [70]. A study also concluded that residents in buildings could save an average of 23% of their cooling costs if the reflectivity of the roof increases [69]. A reflective roof is a design concept that aims to reduce the heat gain from solar absorption through building roofs during sunny days. Some research show that during hot days, the temperature of regular dark roofs reaches 66 °C or higher. By contrast, a reflective roof under a similar environmental condition maintains its temperature at about 28 °C. Control of reflectivity in animal biophotonics gives numerous inspirations for reflective roofs designs, e.g. hairs on edelweiss bracts [71] and the scales of Cyphochilus spp. Beetles. Ye et al. [72] demonstrated that poplar leaf hair, which is the white coating on the lower surface of the leaf, provides the leaf with an efficient cooling effect. They designed a highly reflective superhydrophobic white coating using a similar structure to the leaf hairs. The film has high reflectance in visible and infrared wavelengths. High reflectance of the lower surface mainly originates from the hair layer of the lower surface. Inspired by the structure of the leaf hairs on the lower surface, they fabricated a series of hollow fibrous polymer films with high reflectance using coaxial electro-spinning technology.

3.7. Radiative cooling façade inspired by green leaves and Saharan silver ants

Radiative cooling is another radiation approach that can be easily found in the natural world. An instant example can be the forming of mist on a surface (such as leaves) exposed to a cloudless night sky even when the surrounding temperature is higher than the freezing point of the water. This unusual natural phenomenon can be explained by the fact that a sky-facing surface dissipates heat effectively by strongly emitting radiation to the cold universe (the temperature of the universe is only 3 K) [73] through the Earth's atmosphere transparency window, also known as the atmospheric window, with wavelength between 8 and 13 μm. As a result, the surface can maintain a temperature well below the ambient temperature to facilitate the water nucleation and condensation. The radiation of wavelength in the range of $8 \sim 13$ μm can pass through the atmospheric window to the universe directly without significant absorption and re-emission. Some pioneering researchers realized the atmospheric window coincides with the peak thermal radiation of a black body defined by Plank's law at the ambient temperature (at around 300 K). Therefore, materials those can strongly and selectively emit radiation within the atmospheric window could preserve a sub-ambient temperature at night. This is the idea of passive nighttime radiative cooling [74-77]. Therefore, the radiative cooling technology itself is a bio-inspired cooling technology.

Compared to nighttime radiative cooling, daytime radiative cooling is more challenging; solar radiation needs to be carefully handled [78]. At the early stage, a lot of researchers try to get daytime radiation cooling, but all failed. Recently, scientists and engineers renewed their interest in this topic because a breakthrough in daytime radiative cooling was demonstrated by Raman et al. [79] who used a photonic radiative cooler which has a high reflectance in the solar spectrum and a high emissivity in the atmospheric window wavelength. They also conclude that a daytime radiative cooler needs to radiate strongly within the infrared atmospheric transparency window ($8 \sim 13$ μm) and to reflect strongly within the solar spectrum simultaneously so that net heat flux can be negative and cool the rooms. However, materials with natural high-infrared emissive materials also tend to absorb visible wavelengths.

It should be noticed that the material used for radiative cooling also needs to have high reflectivity in solar radiation wavelengths. However, in this paper, the reflective roof/walls and radiative roof are classified as two radiation mechanisms. Here are the differences: (1) Reflective roof/wall focuses on reflecting solar radiation and obtain energy-saving effect in the daytime, as for radiative cooling roof, which emits solar radiation to outer space and can achieve both daytime and nighttime cooling effect. (2) A reflective surface can be used in other building envelopes such as walls or windows (when the coating is visible transmittance). (3) Reflective roofs cannot lower surface temperature more than the ambient temperature (heat prevention/reduction); however, radiative cooling can provide a sub-ambient temperature (heat dissipation). Therefore, radiative cooling can save more energy compared to the reflective roof technique.

Living nature, such as green plants and trees, have a similar problem of controlling temperature. However, the temperatures of green leaves rarely reach or even exceed 40 °C because the photosynthesis process has maximum efficiency when the temperature is between about 20 °C and 30 °C [80]. In 2008, Henrion et al. [80] discovered how the trees survive in intensive solar radiation by cooling themselves and concluded that the green leaves absorb the minimum useful radiation and emit efficient infrared thermal to the outer space. They attribute these properties to the leaves, effectively emit radiation of wavelengths between 6 and 10 μm because of the properties of tannin and cellulose. The unique thermal rectification in green plants also attracts some researches recently. Li et al. [81] engineered the natural wood with complete delignification followed by mechanical pressing. Similarly, they also conclude the special emission properties are due to cellulose whose molecular vibration and stretching facilitate intense emission in the mid-infrared region ($8 \sim 13$ μm), while the multiscale fibers and channels function as randomized and disordered scattering elements for an strong broadband reflection at all visible wavelengths. The heat flux emitted by the cooling wood exceeds the absorbed solar irradiance, contribute to passive sub-ambient radiative cooling for both day and night.

Cataglyphis bombycine, namely Saharan silver ants, live in an extremely hot desert climate (60–70 °C). Shi et al. [82] discovered that the densely patterned triangular hairs was the reason for their silvery appearance. The special hairs have two thermoregulatory effects: 1) Enhance the broadband reflectivity over the visible and near-infrared (NIR) range by total internal reflection, and 2) enlarge the emissivity in the mid-infrared region, which can enhance heat dissipation efficiently, and keep body temperature much lower than the ambient surroundings. Based on the discovery of survivor of Saharan silver ants in extreme climates, the principles are basically the working principles of passive radiative cooling. Therefore, Shi et al. [83] demonstrated a synthetic approach for the creation of biomimetic nanostructures (triangular arrays) for radiative cooling via a nano-3D lithography technique. Their results showed that the artificially fabricated material could enhance the reflectivity in the visible and NIR region from $\sim 10\%$ to $\sim 30\%$. Thus, passive cooling should be a potential trend for further developing cooling technologies for buildings.

3.8. Transparent building elements - the eyeballs of moths-based design in smart window

Smart window, an advanced window technology, modulates the solar radiation whereby the energy consumption in buildings can be mitigated [84-87]. Its principle is to block the excess solar energy during hot seasons but maximize the transmitted solar radiation during winter. Thermochromic smart window is the most famous smart window that has been largely investigated. The requirements of an ideal thermochromic smart window are high luminous transmittance (T_{lum}) and a large solar modulation ability (ΔT_{sol}) [85]. Numerous efforts have been made to increase T_{lum} and ΔT_{sol} including some bio-inspired technologies. Bioinspired structures such as antireflection surfaces have been applied for smart windows application to enhance the performances. Inspired by the eyeballs of moths which contain nanostructures as hexagonally arranged circular paraboloid cones, Taylor et al. [88] first used finite-difference-time-domain simulation to analyze the moth-eye antireflection surfaces and demonstrated that SiO_2 nanoarrays ($\sim$130 nm periodicity) with VO_2 nanocoating could enhance the ΔT_{sol} up to 15% and obtain a high visible transmittance of 70%. Later, based on the simulation results above, Qian et al. [89] fabricated VO_2 films with moth-eye antireflection nanostructures via reactive ion etching approach to enhance the VO_2 thermochromic smart windows performances. Compared with the planar VO_2 film, the bioinspired nano-patterned antireflection surfaces showed about 10% enhancement of T_{lum} and 24.5% increase in ΔT_{sol}.

4. Natural convection in architectural scale

Researchers aim to investigate the possibilities of employing the ideas of the active and passive fluid flow as well as the air ventilation management found in social insects on building technology to achieve energy saving [7,8,37,90]. In this section, the convective mechanism of the spieces that are settled in extreme climates and the related bio-spired technologies are discussed.

4.1. Termite mounds which enhances natural convection

Residing on desert ground of temperature variation as large as 50 °C, termites living in their mounds manage to keep the average temperature within their nest at around 28 °C [91]. This phenomenon has inspired some preliminary efforts in harnessing the superior thermal properties of the termite mounds and putting them into building application. For instance, architect Mick Pearce got his inspiration from the mounds in his design of Eastgate Center building in Zimbabwe's capital Harare [92]. The chimneys along the roof resembles the chimneys at the top part of the termite mounds, and the interior atrium facilitates natural convection like the mounds. Traces of termite mound inspiration can also be found in his line of architectures, such as the wavy ceiling in the atrium of the second Municipal Office Building in Melbourne [93].

After an extensive study of architectures and functional organizations of termite mounds, Turner and Soar claimed that there were more advantageous elements that can be extracted from termite mounds for building design than air-handling systems [92]. According to them, termites have high thermal resistance against extreme climate because they can actively control the openings at the top and bottom of the mound, and the intricate design of the mounds facilitates thermoregulation, ventilation and gaseous exchange effectively. Termite mounds consist of three major parts: 1. Egress tunnels and surface conduits, where the strong wind-driven forced convection occurs; 2. Reticulum, where mixed forced convection and natural convection dominates; 3. Nest, chimney and subterranean tunnels, where natural convection occurs mostly. Indeed, some beehives and ant nests also employ similar strategy of active covering or opening air passages to control the temperature and air ventilation inside the nest [38]. Inspired by this configuration, porous walls, which allows mass and thermal energy exchange, are developed for future application in building envelopes. A similar idea has already been applied to walls in existing buildings. The administration headquarters of German RWE AG used double glass curtain wall, which has a layer of air sandwiched between two glasses with controllable valves to promote air ventilation beneath the exterior walls, thereby regulating the indoor temperature [94].

5. Thermal management

Current bio-inspired cooling technologies have been advanced and their potential implementation in buildings have been widely demonstrated. However, thermal comfort, indoor air quality (IAQ) and energy efficiency can only be achieved with a well-developed thermal control system [8,95-97]. The most common example is probably the simple thermostat technology, by which heating and cooling units operate to maintain the air-conditioned spaces within a desired set-point range based on the real-time indoor condition. Time-lag of these equipment and late thermal response of the spaces are the major reasons responsible for thermal overshoots and energy waste. The increasing concerns about building energy efficiency has led to the rapid development of bionic green buildings worldwide utilizing the animal thermoregulation strategies, which is ought to create sustainable designs. In this section, a number of strategies inspired by the nature are discussed. Although these strategies involve control and optimization theories, which can also be applied in other fields of applications, we shall focus on their application on cooling purpose in buildings in this paper. They are classified as the system application scale as in Table 1.

5.1. Artificial neural network mimicking the brain and the neural systems

In the natural, every organism has its own thermal control system which governs the heat transfer process between its body and the environment, thereby preventing them from overheating and hypothermia. Cold-blooded animals like alligators and desert iguanas regulate their body temperature by altering the metabolic activity [98-100]. Varying their heartbeat pattern allows them to control heat and cold generation effectively while achieving the least energy consumption [8]. Some species avoid heat losses by manipulating blood circulation [101,102]. For instance, marine iguanas stopped blood flowing through the lungs in cold temperature. Even plants response indirectly to heat [103]. Most plants rely on sunlight for living but too much solar energy may burn up the plants. Some plants like sunflower and cotton plants limit the amount of in-coming heat by tracing after or deviate from the sunlight using their photo-sensory organs [104]. For human, the body temperature is always maintained stably at around 37 °C, but it may differ slightly depending on the physical conditions of individuals. Infants sometimes have a higher normal body temperature than adults. Our brain acts as a biological thermal control system which deicides the optimal body temperature and keeps us at the desired stage using various heat regulation strategies in our body. When we are sick, our body temperature tends to go above or below normal giving an alert that our body physical function has problems. At only 0.5 °C above normal, it is already called a fever. The symptoms include shivering, sweating, hyperalgesia, problems concentrating, etc. These thermal management strategies have inspired scientists and researchers to investigate potential implementation methods for existing building energy systems, among which Artificial Neural Network (ANN) is believed to be the most broadly adapted method.

ANNs are information processes systems inspired by neural systems in biological brains to predict energy consumptions in buildings [95,105]. ANN is basically a network of neurons in many layers that are categorized in three areas, namely input, hidden and output. The input neurons form an input layer which receives signals from outside while the output neurons form the last layer called the output layer which supplies the results evaluated by the system. It can be many hidden layers between the input and output layers. The number of hidden layers determine the complexity of a system. Neurons on adjoint layers are connected in which transfer functions are employed. The computing systems are trained using previously recorded data representing the relationship between input and output variables, thereby being able to foresee how a system behavior under various conditions [105]. In building thermal control, ANN models can precisely calculate the start and stop times of the air conditioning units before the indoor temperature reaches the thermostat setpoint whereby temperature overshoots and the associated energy waste can be significantly reduced [106]. Besides thermal comfort, other control objectives include energy efficiency [107,108], IAQ [109], and operating cost [110,111].

5.2. Evolution: Genetic algorithms

Genetic algorithms (GAs) are computational models inspired by natural evolution [112]. In a GA, a population of individuals with different genome, which represents parameters to be optimized, is evolved through the process of natural selection. The individuals with better fitness will survive and reproduce the next generation. Mutation might occur during the process to bring in additional possible variations. The process ends when the number of iterations reaches the preset maximum or a specific fitness has been generated. GA has been widely adopted in improving the building overall design [113-119]. According to Hamdy et al. [120], GA is the most frequently used optimization algorithms in more than 200 building design optimization studies, in which twenty one design variables have been studied with the goal of optimizing the thermal performance and energy efficiency of residential buildings [113]. Since thermal comfort and energy expenditure are contradicting criteria in indoor environment, the objective function is usually described by the thermal discomfort degree-hours and the energy consumption of air-conditioners. Zhang et al. [119] have developed a multi-objective GA to optimize the thermal and daylight performance of school buildings. Through the optimization process, different design parameters, including orientation, depth of classroom, depth of corridor, window-to-wall ratio, glazing material and shading type were investigated. Their results showed that the energy demand for heating and lighting can be reduced by up to 28%, thermal discomfort in hot season by 9–23%, and the useful daytime illuminance can be raised by 15–63%. Other multi-objective GA models have also been developed successfully [114,121,122]. Carlucci et al. [114] developed an optimization method to address a four-dimensional problem which are: (1) thermal discomfort during winter, (2) thermal discomfort during summer, (3) visual discomfort due to glare, and (4) visual discomfort due to an inappropriate quantity of daylight. The objectives were minimized with U-values of external walls, roof, floor and glazing units, visible light transmittance of glazing units, solar shading devices and windows opening as design variables [114]. Besides typical building design parameters, GA can also be employed in determining the placement of building integrated photovoltaics (BIPV) [118].

GA was also adopted in optimizing the use of various building systems to achieve better comfort and reduce energy consumption. It can be applied in underfloor heating system [123] and HVAC system [124-126]. The typical proportional and integral (PI) controller for HVAC systems would be optimized by GA [124]. The overshoot and settling time were largely reduced when compared with using Ziegler-Nichols method. In addition, a more advanced adaptive fuzzy logic controller for an air conditioning system would also be developed by using GA and evolutionary strategies [125,127]. Chang et al. [126] has optimized the chiller loadings to minimize the chiller plant energy consumption by the Lagrangian method and GA. The results showed that GA can save 20% to 74% of electrical energy compared to the Lagrangian method. GA also showed better convergent ability in low load condition. On the water-side, the water flow rate can be optimized by applying GA on the position of the valves [96]. On the air-side, the velocity and temperature of supply air can be taken as controlled variables to optimize the thermal comfort, head to ankle temperature difference and CO_2 level [128]. Due to its promising performance, it is expected that abundant research and building designs will be generated by using GA in the future.

6. A case study simulation

In order to compare the current developed bio-inspired cooling technologies and to study the feasibility of applying these technologies in a house, a simulation study was conducted using EnergyPlus, an open-source whole-building energy modeling (BEM) engine developed by U.S. Department of Energy. Detailed building physics for air, moisture, and heat transfer were included in EnergyPlus. Radiative and convective heat transfers were treated separately to support modeling of radiant systems and calculation of thermal comfort metrics. Because of its high flexibility, different component-level configuration of HVAC, plant, and refrigeration systems is supported. The transient states of the building were simulated in EnergyPlus, so fast system dynamics and control strategies would be realized. EnergyPlus is tested according to ASHRAE Standard 140, which applies to building energy computer programs that calculate the thermal performance of a building and its mechanical systems. In this section, four simulated bio-inspired cooling technologies including carbon nanotube aerogel coating, passive radiative cooler, thermochromic smart window and evaporative condensers are analyzed by EnergyPlus. These four bio-inspired technologies are considered because they have been experimentally tested, and these technologies have potential to be widely applied in the coming future for improving energy efficiency. Details and performance of each of the four bio-inspired technologies is presented one after another in the following sections. In this study, ASHRAE standard test case 600 was adopted (Fig. 2). Standard test case 600 is the recommended base case for building thermal envelope and fabric load tests according to ASHRAE Standard 140 [129]. It is a room with a rectangular floor plan of 8 m $\times$ 6 m and height of 2.7 m equipped with two double pane windows at size of 3 m $\times$ 2 m on south facing wall. The thermal and material properties for the wall, floor and roof were listed in Table 2. Since the performance of the bio-inspired technologies is highly depended on the weather conditions, three cities were considered: (1) Hong Kong, (2) New York, and (3) Singapore in the simulation study. They are highly civilized cities located in different climate conditions. Hong Kong's climate is sub-tropical, tending towards temperate for nearly half the year, with very mild winters and hot, rainy, and muggy summers. The climate of New York is generally humid continental. Winter temperatures average below freezing during January and February in much of New York State. Singapore is situated near the equator and has a typically tropical climate, with abundant rainfall, high and uniform temperatures, and high humidity all year round. The annual energy

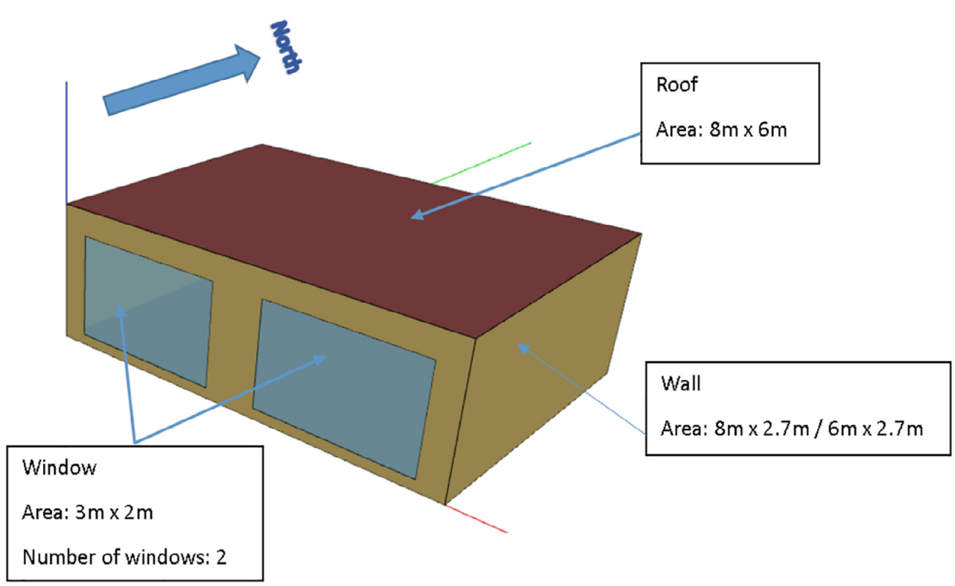

Fig. 2. Schematic diagram of ASHRAE standard test case 600.

Table 2
Thermal and material properties for ASHRAE standard test case 600.

Element	Thermal conductivityW/(m.K)	Thickness, m	U-value, W/(m^2.K)	R-value, (m^2.K)/W	Density, kg/m^3	Heat capacity c_pJ/(kg.K)
Lightweight Case: Exterior Wall (inside to outdoors)						
Interior surface coefficient			8.290	0.121		
Plasterboard	0.160	0.012	13.333	0.075	950.000	840.000
Fiberglass quilt	0.040	0.066	0.606	1.650	12.000	840.000
Wood sidling	0.140	0.009	15.556	0.064	530.000	900.000
Exterior surface coefficient			29.300	0.034		
Lightweight Case: Floor (inside to outdoors)						
Interior surface coefficient			8.290	0.121		
Timber flooring	0.140	0.025	5.600	0.179	650.000	1200.000
Insulation	0.040	1.003	0.040	25.075	0.000	0.000
Lightweight Case: Roof (inside to outdoors)						
Interior surface coefficient			8.290	0.121		
Plasterboard	0.160	0.010	16.000	0.063	950.000	840.000
Fiberglass quilt	0.040	0.112	0.357	2.800	12.000	840.000
Roofdeck	0.140	0.019	7.368	0.136	530.000	900.000
Exterior surface coefficient			29.300	0.034		
Summary: Lightweight Case						
Component	**U,W/m^{2}K**	**Area,m^2**	**UA,W/K**			
Wall	0.5144	63.600	32.715			
Floor	0.0394	48.000	1.892			
Roof	0.3177	48.000	15.253			
Window		12.000	36.000			
Infiltration			18.440			
Total UA (with window)			104.300			
Total UA (without window)			68.300			

Table 3
Annual energy consumptions in three cities of the standard case.

	Cooling Load (kWh)													Annual Energy Consumption (kWh)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	
Hong Kong	428	296	328	413	548	645	768	750	753	879	771	630	7,210	2,403
New York	173	261	314	372	469	665	829	818	744	595	237	211	5,689	1,896
Singapore	882	774	700	689	733	709	703	695	618	753	780	815	8,851	2,950

consumptions in the three cities of the standard case are calculated by assuming the coefficient of performance of the air conditioning system to be 3, and listed in Table 3.

6.1. Performance of carbon nanotube aerogel

The simulated annual cooling load under base case in Hong Kong, New York and Singapore are 7,210 kWh, 5,689 kWh and 8,851 kWh, respectively (see Table 3). According to [32], the thermal conductivity of the carbon nanotube aerogel inspired by polar bear hair can reach as low as 0.023 mW/mK. If the carbon nanotube aerogel was applied to replace fiberglass quilt in the wall, the U-value of the wall can be substantially reduced from 0.5144 W/m^{2}K to 0.3161 W/m^{2}K. The annual cooling load power in Hong Kong, New York and Singapore would change to 6,565 kWh, 5,747 kWh and 7,872 kWh, respectively, with a reduction of 8.94%, −1.03% and 11.06% respectively. This technology works particularly well in tropical and sub-tropical climates, but it may also lead to an increase in energy consumption in other regions. In New York, the outdoor temperature is generally lower than Hong Kong and Singapore. When the outdoor temperature is lower than the indoor set point temperature, a heat loss to the outdoor would reduce the cooling load of the building, so a better insulated wall would reduce such beneficial heat loss in some occasions resulting in higher cooling load.

6.2. Performance of bio-inspired passive radiative cooler

A passive radiative cooler is a passive device that can dissipate heat by strongly and selectively emitting radiation to the cold universe. According to Jeong et al. [76], a passive radiative cooler inspired by Saharan silver ant can provide a net cooling power of 19.7 W/m^2 in a field test in Hong Kong during the daytime. Considering a cooling unit with the same size as the window of 3 m × 2 m installing on the roof, it can reduce the net annual cooling load by 1,035 kWh theoretically. However, the performance of radiative cooler relays on the transparency of the sky that the infrared heat energy can be radiated to the universe. Any blockage between the cooling device and universe will affect the cooling effect. In this study, we considered the cloud coverage among the three cities (data provided by EnergyPlus), while the effect of relative humidity is neglected to simplify the calculation. A more humid air has high infrared absorptivity that lower the cooling effect of the radiative cooler. In general, a place with higher cloud coverage is usually more humid, so the effect of relative humidity would be represented by the cloud coverage. The annual average cloud coverage in Hong Kong, New York and Singapore are 69.68%, 56.24% and 85.63% respectively. Hence, the annual cooling load reduction in Hong Kong, New York and Singapore are 314 kWh (4.35%), 453 kWh (7.97%) and 149 kWh (1.68%) respectively. It can be seen that the radiative cooler would function well in places with dry climate like New York. However, several drawbacks exist and hinder its further practical development. First, most of the designs utilized photonic nanostructures. Large-scale manufacture of the coolers with equal performance is challenging. Second, the long-term maintenance and proper methods to incorporate the coolers into building infrastructure are also big challenges. Any surface dust or air pollutants would reduce the cooling performance of the radiative cooler. Third, in order to achieve the optimal cooling performance, the cooler should be fully exposed to the sky, so that the

Table 4
Summary of annual performance of bio-inspired cooling technologies with standard case.

	Cooling Load Required(kWh)	Cooling LoadReduction(kWh)	Annual EnergyConsumption(kWh)	%Reduction
Standard Case in Hong Kong	**7,210**		**2,403**	
Applying carbon nanotube aerogel	6,565	645	2,188	8.94%
Applying radiative Cooler	6,896	314	2,299	4.35%
Applying Smart Window	6,385	825	2,128	11.44%
Applying above three technologies	5,536	1,674	1,845	23.22%
Applying evaporative condensers	5,536	1,674	775	67.74%
Standard Case in New York	**5,689**		**1,896**	
Applying carbon nanotube aerogel	5,747	−59	1,916	−1.03%
Applying radiative Cooler	5,235	453	1,745	7.97%
Applying Smart Window	5,038	651	1,679	11.44%
Applying above three technologies	4,688	1,000	1,563	17.58%
Applying evaporative condensers	4,688	1,000	657	65.37%
Standard Case in Singapore	**8,851**		**2,950**	
Applying carbon nanotube aerogel	7,872	979	2,624	11.06%
Applying radiative Cooler	8,702	149	2,901	1.68%
Applying Smart Window	7,838	1,013	2,613	11.44%
Applying above three technologies	6,840	2,011	2,280	22.72%
Applying evaporative condensers	6,840	2,011	958	67.53%

cooler can only be installed on horizontal roof. However, the roof area is limited and the cooler cannot meet the cooling requirements of multi-story buildings [77].

6.3. Performance of bio-inspired thermochromic smart window

As discussed in Section 3.8, thermochromic smart window can change its color to block the solar energy from getting indoor during hot seasons and maximize the transmitted solar radiation during winter. Ye et al. [86] has demonstrated the effect of a thermochromic smart window in Hefei, China, showing a reduction in cooling load of a room from 10.2% to 19.9% comparing to ordinary glazing. The annual cooling load reduction was also simulated to be 9.4% for a room with window-to-wall ratio (WWR) of 0.13 [86]. As the WWR for the standard test case 600 is 0.16, two thermochromic smart windows of size of 12 m^2 in total would save 11.44% of power consumption. The transition temperature for smart window in this research is 41.3 °C, which is still quite above the ambient temperature. It is believed that if the transition temperature can be tuned to 14 $\sim$ 20 °C, more energy can be saved [87].

6.4. Performance of bio-inspired evaporative condensers

As discussed previously, evaporative condensers inspired by sweating skin of mammal were reported to reduce up to 58% of the power consumption of the air conditioning system, compared with an air-cooled condenser [26]. For the base case, the coefficient of performance of the air conditioning system is assumed to be 3. With 58% of power reduction, the COP would increase up to 7.14. The annual energy consumption of each bio-inspired cooling technologies and the overall performance are shown in Table 4. With the three building envelope bio-inspired technologies integrated (carbon nanotube aerogel, passive radiative cooler and thermochromic smart window), the annual energy consumption in Hong Kong, New York and Singapore are 1,845 kWh, 1,563 kWh and 2,280 kWh, respectively, while the energy consumption would be reduced to 775 kWh, 657 kWh and 958 kWh, respectively if evaporative condensers are employed. The use of evaporative condensers would be promising but the exposed wet surface on the condensers might cause some health problems. The hot and humid surface is ideal for legionellae to grow and proliferate [130]. Thus, additional care should be given to disinfect the circulating water and biocide has to be dosed in the water.

7. Conclusions

The bio-inspired cooling technologies according to the classification of building elements and application scale were reviewed. Technologies for the improvement of HVAC systems were discussed followed by the review of building element technologies - opaque and transparent building elements. Their heat transfer mechanisms, i.e. conduction, convection, evaporation/phase change and radiation, were also explained. Energy efficient building cannot be achieved effectively by a single technology. Optimization of different cooling technologies by thermal management is essential and some bio-inspired algorithms, e.g. artificial neural network, genetic algorithms were compared. A case study was conducted using EnergyPlus simulation to analyze the performance of different bio-inspired technologies in three different cities. Four types of bio-inspired technologies regarding to carbon nanotube aerogel, passive radiative cooler, thermochromic smart window and evaporative condensers were considered and showed their promising capabilities for future applications. Drawbacks and limitations in applying these technologies were discussed.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] U.S. Energy Information Administration (EIA), How much energy is consumed in residential and commercial buildings in the United States? (2019). Retrieved December 14, 2019 from http://www.eia.gov/tools/faqs/faq.cfm?id=86&t=1.
[2] European Commission, Nearly zero-energy buildings. (2019). Retrieved December 14, 2019 from https://ec.europa.eu/energy/en/topics/energy-efficiency/energy-performance-of-buildings/nearly-zero-energy-buildings.
[3] Electrical and Mechanical Services Department, HKSAR, Hong Kong energy end-use data 2019. (2019). Retrieved December 14, 2019 from https://www.emsd.gov.hk/filemanager/en/content_762/HKEEUD2019.pdf.

[4] L. Pérez-Lombard, J. Ortiz, C. Pout, A review on buildings energy consumption information, Energy Build. 40 (2008) 394–398.
[5] S.B. Sadineni, S. Madala, R.F. Boehm, Passive building energy savings: A review of building envelope components, Renew. Sustain. Energy Rev. 15 (2011) 3617–3631.
[6] I.G. Capeluto, Energy performance of the self-shading building envelope, Energy Build. 35 (2003) 327–336.
[7] Y. Yuan, X. Yu, X. Yang, Y. Xiao, B. Xiang, Y. Wang, Bionic building energy efficiency and bionic green architecture: A review, Renew. Sustain. Energy Rev. 74 (2017) 771–787.
[8] C. Martín-Gómez, A. Zuazua-Ros, J. Bermejo-Busto, E. Baquero, R. Miranda, C. Sanz, Potential strategies offered by animals to implement in buildings' energy performance: Theory and practice, Front. Architect. Res. 8 (2019) 17–31.
[9] Z. Huang, Y. Hwang, R. Radermacher, Review of nature-inspired heat exchanger technology, Int. J. Refrig. 78 (2017) 1–17.
[10] P.K. Phillips, J.E. Heath, Heat exchange by the pinna of the african elephant, Loxodonta africana, Comp. Biochem. Physiol. A Physiol. 101 (1992) 693–699.
[11] X.-Q. Wang, P. Xu, A.S. Mujumdar, C. Yap, Flow and thermal characteristics of offset branching network, Int. J. Therm. Sci. 49 (2010) 272–280.
[12] D. Pence, Reduced pumping power and wall temperature in microchannel heat sinks with fractal-like branching channel networks, Microscale Thermophys. Eng. 6 (2003) 319–330.
[13] Y. Chen, P. Cheng, Heat transfer and pressure drop in fractal tree-like microchannel nets, Int. J. Heat Mass Transf. 45 (2002) 2643–2648.
[14] S.M. Senn, D. Poulikakos, Laminar mixing, heat transfer and pressure drop in tree-like microchannel nets and their application for thermal management in polymer electrolyte fuel cells, J. Power Sources 130 (2004) 178–191.
[15] A.Y. Alharbi, D.V. Pence, R.N. Cullion, Thermal Characteristics of Microscale Fractal-Like Branching Channels, J. Heat Transfer 126 (2004) 744–752.
[16] X.-Q. Wang, A.S. Mujumdar, C. Yap, Thermal characteristics of tree-shaped microchannel nets for cooling of a rectangular heat sink, Int. J. Therm. Sci. 45 (2006) 1103–1112.
[17] F.J. Hong, P. Cheng, H. Ge, G.T. Joo, Conjugate heat transfer in fractal-shaped microchannel network heat sink for integrated microelectronic cooling application, Int. J. Heat Mass Transf. 50 (2007) 4986–4998.
[18] G.A. Bartholomew, R.C. Lasiewski, E.C. Crawford, Patterns of panting and gular flutter in cormorants, pelicans, owls, and doves, The Condor. 70 (1968) 31–34.
[19] F.A. Ryser, Birds of the Great Basin: a natural history, University of Nevada Press (1985) 28–30.
[20] G.C. Whittow, Regulation of body temperature, in: Avian Physiology, Springer, (1986) 221–252.
[21] W.R. Dawson, C.D. Fisher, Responses to Temperature by the Spotted Nightjar (Eurostopodus guttatus), The Condor. 71 (1969) 49–53.
[22] R.C. Lasiewski, G.A. Bartholomew, Evaporative cooling in the poor-will and the tawny frogmouth, The Condor. 68 (1966) 253–262.
[23] R.K.B. Gallegos, R.N. Sharma, Flags as vortex generators for heat transfer enhancement: Gaps and challenges, Renew. Sustain. Energy Rev. 76 (2017) 950–962.
[24] Y. Hwang, R. Radermacher, W. Kopko, An experimental evaluation of a residential-sized evaporatively cooled condenser, Int. J. Refrig 24 (2001) 238–249.
[25] K. Harby, D.R. Gebaly, N.S. Koura, M.S. Hassan, Performance improvement of vapor compression cooling systems using evaporative condenser: An overview, Renew. Sustain. Energy Rev. 58 (2016) 347–360.
[26] M.G. Vrachopoulos, A.E. Filios, G.T. Kotsiovelos, E.D. Kravvaritis, Incorporated evaporative condenser, Appl. Therm. Eng. 27 (2007) 823–828.
[27] J. Ju, H. Bai, Y. Zheng, T. Zhao, R. Fang, L. Jiang, A multi-structural and multi-functional integrated fog collection system in cactus, Nat. Commun. 3 (2012) 1247.
[28] A.R. Parker, C.R. Lawrence, Water capture by a desert beetle, Nature 414 (2001) 33.
[29] X. Ma, P. Cheng, X. Quan, Simulations of saturated boiling heat transfer on bio-inspired two-phase heat sinks by a phase-change lattice Boltzmann method, Int. J. Heat Mass Transf. 127 (2018) 1013–1024.
[30] L. Cafsia, Plyskin; insulating façade panel based on Biomimicry of the polar bear skin and fur, in: IABSE Symposium Report, International Association for Bridge and Structural Engineering (2017) 58–59.
[31] H.-J. Zhan, K.-J. Wu, Y.-L. Hu, J.-W. Liu, H. Li, X. Guo, J. Xu, Y. Yang, Z.-L. Yu, H.-L. Gao, X.-S. Luo, J.-F. Chen, Y. Ni, S.-H. Yu, Biomimetic Carbon Tube Aerogel Enables Super-Elasticity and Thermal Insulation, Chem 5 (7) (2019) 1871–1882.
[32] C. Chen, L. Hu, Super Elastic and Thermally Insulating Carbon Aerogel: Go Tubular Like Polar Bear Hair, Matter 1 (1) (2019) 36–38.
[33] R.H. Drent, B. Stonehouse, Thermoregulatory responses of the peruvian penguin, Spheniscus humboldti, Comp. Biochem. Physiol. A Physiol. 40 (1971) 689–710.
[34] C. Dawson, J.F.V. Vincent, G. Jeronimidis, G. Rice, P. Forshaw, Heat Transfer through Penguin Feathers, J. Theor. Biol. 199 (1999) 291–295.
[35] A. Aslam, Investigating the Energy Efficiency of Biomimetic Facades based on Penguin Feathers for attaining Thermal Comfort in Interiors, in: Proceedings of the 2nd Conference: People and Buildings, London, UK, (2012) 1-6.
[36] R. Sudarsan, C. Thompson, P.G. Kevan, H.J. Eberl, Flow currents and ventilation in Langstroth beehives due to brood thermoregulation efforts of honeybees, J. Theoret. Biol. 295 (2012) 168–193.
[37] R.E. Bonoan, R.R. Goldman, P.Y. Wong, P.T. Starks, Vasculature of the hive: heat dissipation in the honey bee (Apis mellifera) hive, Naturwissenschaften 101 (2014) 459–465.
[38] J. Jones, B. Oldroyd, Nest Thermoregulation in Social Insects, Adv. Insect Physiol. 33 (2006) 153–191.
[39] L. Frandsen, Double-skin insulated building panel, Google Patents (1976).
[40] T. Price, R.L. Timbrook, Structural honeycomb panel building system, Google Patents (2001).
[41] M. Boukendil, A. Abdelbaki, Z. Zrikem, Detailed numerical simulation of coupled heat transfer by conduction, natural convection and radiation through double honeycomb walls, Build. Simul. 5 (2012) 337–344.
[42] M. Wu, J. Liu, Study on Thermal Performance of Single-layer and Multi-layer Stone Aluminum Honeycomb Composite Panels, J. Phys. Conf. Ser. 1300 (2019) 12002.
[43] M.M. Almutairi, M. Osman, I. Tlili, Thermal Behavior of Auxetic Honeycomb Structure: An Experimental and Modeling Investigation, J. Energy Resour. Technol. 140 (2018) 122908 (8 pages).
[44] J.P. Vitale, G. Francucci, A. Stocchi, Thermal conductivity of sandwich panels made with synthetic and vegetable fiber vacuum-infused honeycomb cores, J. Sandwich Struct. Mater. 19 (2017) 66–82.
[45] K.M. Al-Obaidi, M.A. Ismail, H. Hussein, A.M.A. Rahman, Biomimetic building skins: An adaptive approach, Renew. Sustain. Energy Rev. 79 (2017) 1472–1491.
[46] S. Cui, Y. Hu, Z. Huang, C. Ma, L. Yu, X. Hu, Cooling performance of bio-mimic perspiration by temperature-sensitive hydrogel, Int. J. Therm. Sci. 79 (2014) 276–282.
[47] S. Cui, C. Ahn, M.C. Wingert, D. Leung, S. Cai, R. Chen, Bio-inspired effective and regenerable building cooling using tough hydrogels, Appl. Energy 168 (2016) 332–339.
[48] A.C.C. Rotzetter, C.M. Schumacher, S.B. Bubenhofer, R.N. Grass, L.C. Gerber, M. Zeltner, W.J. Stark, Thermoresponsive polymer induced sweating surfaces as an efficient way to passively cool buildings, Adv. Mater. 24 (2012) 5352–5356.
[49] K.M. Al-Obaidi, M. Azzam Ismail, H. Hussein, A.M. Abdul Rahman, Biomimetic building skins: An adaptive approach, Renew. Sustain. Energy Rev. 79 (2017) 1472–1491.
[50] D.N. Nkwetta, F. Haghighat, Thermal energy storage with phase change material—A state-of-the art review, Sustain. Cities Soc. 10 (2014) 87–100.
[51] L. Kancane, R. Vanaga, A. Blumberga, Modeling of Building Envelope's Thermal Properties by Applying Phase Change Materials, Energy Procedia 95 (2016) 175–180.
[52] R.A. Young, Fat, energy and mammalian survival, Integr. Comp. Biol. 16 (1976) 699–710.
[53] R.C. Dunkin, W.A. McLellan, J.E. Blum, D.A. Pabst, The ontogenetic changes in the thermal properties of blubber from Atlantic bottlenose dolphin Tursiops truncatus, J. Exp. Biol. 208 (2005) 1469–1480.
[54] H. Nazir, M. Batool, F.J. Bolivar Osorio, M. Isaza-Ruiz, X. Xu, K. Vignarooban, P. Phelan, A.M. Kannan Inamuddin, Recent developments in phase change materials for energy storage applications: A review, Int. J. Heat Mass Transf. 129 (2019) 491–523.
[55] F. Kuznik, D. David, K. Johannes, J.-J. Roux, A review on phase change materials integrated in building walls, Renew. Sustain. Energy Rev. 15 (2011) 379–391.
[56] N. Soares, J.J. Costa, A.R. Gaspar, P. Santos, Review of passive PCM latent heat thermal energy storage systems towards buildings' energy efficiency, Energy Build. 59 (2013) 82–103.
[57] A. Pasupathy, R. Velraj, R.V. Seeniraj, Phase change material-based building architecture for thermal management in residential and commercial establishments, Renew. Sustain. Energy Rev. 12 (2008) 39–64.
[58] P. Schossig, H.M. Henning, S. Gschwander, T. Haussmann, Micro-encapsulated phase-change materials integrated into construction materials, Sol. Energy Mater. Sol. Cells 89 (2005) 297–306.
[59] L. Shilei, F. Guohui, Z. Neng, D. Li, Experimental study and evaluation of latent heat storage in phase change materials wallboards, Energy Build. 39 (2007) 1088–1091.
[60] J. Yi, Demonstration building with ultra-low energy consumption in Tsinghua University, Hv & Ac. (2004) 20.
[61] D.W. Hawes, D. Banu, D. Feldman, The stability of phase change materials in concrete, Sol. Energy Mater. Sol. Cells 27 (1992) 103–118.
[62] D.W. Hawes, D. Feldman, Absorption of phase change materials in concrete, Sol. Energy Mater. Sol. Cells 27 (1992) 91–101.
[63] M. Hadjieva, R. Stoykov, T.Z. Filipova, Composite salt-hydrate concrete system for building energy storage, Renewable Energy 19 (2000) 111–115.
[64] D. Zhang, Z. Li, J. Zhou, K. Wu, Development of thermal energy storage concrete, Cem. Concr. Res. 34 (2004) 927–934.
[65] A. Figueiredo, J. Lapa, R. Vicente, C. Cardoso, Mechanical and thermal characterization of concrete with incorporation of microencapsulated PCM for applications in thermally activated slabs, Constr. Build. Mater. 112 (2016) 639–647.
[66] K. Muruganantham, P. Phelan, P. Horwath, D. Ludlam, T. McDonald, Experimental investigation of a bio-based phase-change material to improve building energy performance, ASME 2010 4th International Conference on Energy Sustainability, ES 2010. 1 (2010) 979–984.
[67] M.C. Floros, K.L.C. Kaller, K.D. Poopalam, S.S. Narine, Lipid derived diamide phase change materials for high temperature thermal energy storage, Sol. Energy 139 (2016) 23–28.

[68] T. Lee, Y. Lee, H.L. Lee, Y.R. Syue, Y.H. Chiu, J.Y. Liou, Y. Sen Sun, Bio-inspired phase change materials designed for high specific heat of solid phase, Thermochim Acta 591 (2014) 61–67.
[69] P. Meenakshi, M. Selvaraj, Bismuth titanate as an infrared reflective pigment for cool roof coating, Sol. Energy Mater. Sol. Cells 174 (2018) 530–537.
[70] H. Akbari, S. Konopacki, M. Pomerantz, Cooling energy savings potential of reflective roofs for residential and commercial buildings in the United States, Energy. 24 (1999) 391–407.
[71] J.P. Vigneron, M. Rassart, Z. Vértesy, K. Kertész, M. Sarrazin, L.P. Biró, D. Ertz, V. Lousse, Optical structure and function of the white filamentary hair covering the edelweiss bracts, Physical Review E - Statistical, Nonlinear, and Soft Matter Physics. 71 (2005) 011906.
[72] C. Ye, M. Li, J. Hu, Q. Cheng, L. Jiang, Y. Song, Highly reflective superhydrophobic white coating inspired by poplar leaf hairs toward an effective "cool roof", Energy Environ. Sci. 4 (2011) 3364–3367.
[73] L. Zhu, A.P. Raman, S. Fan, Radiative cooling of solar absorbers using a visibly transparent photonic crystal thermal blackbody, Proc. Natl. Acad. Sci. 112 (2015) 12282–12287.
[74] S.Y. Jeong, C.Y. Tso, M. Zouagui, Y.M. Wong, C.Y.H. Chao, A numerical study of daytime passive radiative coolers for space cooling in buildings, Build. Simul. 11 (2018) 1011–1028.
[75] M.M. Hossain, M. Gu, Radiative cooling: Principles, progress, and potentials, Adv. Sci. 3 (2016) 1500360.
[76] S.Y. Jeong, C.Y. Tso, Y.M. Wong, C.Y.H. Chao, B. Huang, Daytime passive radiative cooling by ultra emissive bio-inspired polymeric surface, Sol. Energy Mater. Sol. Cells 206 (2020) 110296.
[77] X. Lu, P. Xu, H. Wang, T. Yang, J. Hou, Cooling potential and applications prospects of passive radiative cooling in buildings: The current state-of-the-art, Renew. Sustain. Energy Rev. 65 (2016) 1079–1097.
[78] Y. Zhai, Y. Ma, S.N. David, D. Zhao, R. Lou, G. Tan, R. Yang, X. Yin, Scalable-manufactured randomized glass-polymer hybrid metamaterial for daytime radiative cooling, Science 355 (2017) 1062–1066.
[79] A.P. Raman, M.A. Anoma, L. Zhu, E. Rephaeli, S. Fan, Passive radiative cooling below ambient air temperature under direct sunlight, Nature 515 (7528) (2014) 540–544.
[80] W. Henrion, H. Tributsch, Optical solar energy adaptations and radiative temperature control of green leaves and tree barks, Sol. Energy Mater. Sol. Cells 93 (2009) 98–107.
[81] T. Li, Y. Zhai, S. He, W. Gan, Z. Wei, M. Heidarinejad, D. Dalgo, R. Mi, X. Zhao, J. Song, J. Dai, C. Chen, A. Aili, A. Vellore, A. Martini, R. Yang, J. Srebric, X. Yin, L. Hu, A radiative cooling structural material, Science 364 (2019), 760 LP – 763.
[82] N.N. Shi, C.C. Tsai, F. Camino, G.D. Bernard, N. Yu, R. Wehner, Keeping cool: Enhanced optical reflection and radiative heat dissipation in Saharan silver ants, Science 349 (2015) 298–301.
[83] N.N. Shi, C.-C. Tsai, F. Camino, G.D. Bernard, R. Wehner, N. Yu, Radiative cooling nano-photonic structures discovered in saharan silver ants and related biomimetic metasurfaces, in: CLEO: QELS_Fundamental Science, Optical Society of America (2016) FTh3B-1.
[84] Y. Zhang, C.Y. Tso, J.S. Iñigo, S. Liu, H. Miyazaki, C.Y.H. Chao, K.M. Yu, Perovskite thermochromic smart window: Advanced optical properties and low transition temperature, Appl. Energy 254 (2019) 113690.
[85] Y. Ke, C. Zhou, Y. Zhou, S. Wang, S.H. Chan, Y. Long, Emerging thermal-responsive materials and integrated techniques targeting the energy-efficient smart window application, Adv. Funct. Mater. 28 (2018) 1800113.
[86] H. Ye, L. Long, H. Zhang, B. Xu, Y. Gao, L. Kang, Z. Chen, The demonstration and simulation of the application performance of the vanadium dioxide single glazing, Sol. Energy Mater. Sol. Cells 117 (2013) 168–173.
[87] S. Hoffmann, E.S. Lee, C. Clavero, Examination of the technical potential of near-infrared switching thermochromic windows for commercial building applications, Sol. Energy Mater. Sol. Cells 123 (2014) 65–80.
[88] A. Taylor, I. Parkin, N. Noor, C. Tummeltshammer, M.S. Brown, I. Papakonstantinou, A bioinspired solution for spectrally selective thermochromic VO2 coated intelligent glazing, Opt. Express 21 (2013) A750–A764.
[89] X. Qian, N. Wang, Y. Li, J. Zhang, Z. Xu, Y. Long, Bioinspired multifunctional vanadium dioxide: improved thermochromism and hydrophobicity, Langmuir 30 (2014) 10766–10771.
[90] M. Bollazzi, F. Roces, The thermoregulatory function of thatched nests in the South American grass-cutting ant, Acromyrmex heyeri, Journal of Insect Science (Online) 10 (2010) 137.
[91] J. Zhao, Y. Xu, Ecological wisdom inspired from termite mounds. Analysis on biomimetric design of Zimbabwe Eastgate Center, Building Science, 2(4) (2010) paper no. 2010-02.
[92] J.S. Turner, R.C. Soar, in: Beyond biomimicry: What termites can tell us about realizing the living building, Loughborough University, 2008, pp. 1–18.
[93] M. Pearce, Study on the Aesthetics and physiology of Melbourne city council's green office block, Ch2. (2012) 9.
[94] H. Yue, Analysis of the Respiratory Double Curtain Wall, Type and Energy Saving Results (2006) 2.
[95] R. Kumar, R.K. Aggarwal, J.D. Sharma, Energy analysis of a building using artificial neural network: A review, Energy Build. 65 (2013) 352–358.
[96] V. Congradac, F. Kulic, HVAC system optimization with CO2 concentration control using genetic algorithms, Energy Build. 41 (2009) 571–577.
[97] M. Lv, X. Yang, The role of simulation in preventing indoor air pollution: a foregone conclusion?, in: IOP Conference Series: Materials Science and Engineering, IOP Publishing, (2019) 22005.
[98] F. Seebacher, C.E. Franklin, Redistribution of blood within the body is important for thermoregulation in an ectothermic vertebrate (Crocodylus porosus), J. Comp. Physiol. B. 177 (2007) 841–848.
[99] E.N. Smith, S. Robertson, D.G. Davies, Cutaneous blood flow during heating and cooling in the American alligator, Am. J. Physiol. 235 (1978) R160–R167.
[100] J.S. Turner, C.R. Tracy, Body size and the control of heat exchange in alligators, J. Therm. Biol 10 (1985) 9–11.
[101] L.A. Baker, F.N. White, Redistribution of cardiac output in response to heating in Iguana iguana, Comp. Biochem. Physiol. 35 (1970) 253–262.
[102] F.N. White, Temperature and the Galapagos marine iguana—Insights inso reptilian thermoregulation, Comp. Biochem. Physiol. A Physiol. 45 (1973) 503–513.
[103] J. Ehleringer, I. Forseth, Solar tracking by plants, Science 210 (1980) 1094–1098.
[104] C.F. Gay, J.W. Yerkes, J.H. Wilson, Performance advantages of two-axis tracking for large flat-plate photovoltaic energy systems, in: 16th Photovoltaic Specialists Conference (1982) 1368–1371.
[105] E. Asadi, M.G. Da Silva, C.H. Antunes, L. Dias, L. Glicksman, Multi-objective optimization for building retrofit: A model using genetic algorithm and artificial neural network and an application, Energy Build. 81 (2014) 444–456.
[106] J.W. Moon, S.K. Jung, J.-J. Kim, Application of ANN (artificial-neural-network) in residential thermal control, in: Proceedings of the Eleventh International IBPSA Conference, Glasgow, Scotland (2009) 27–30.
[107] P.M. Ferreira, A.E. Ruano, S. Silva, E.Z.E. Conceicao, Neural networks based predictive control for thermal comfort and energy savings in public buildings, Energy Build. 55 (2012) 238–251.
[108] H. Huang, L. Chen, E. Hu, A new model predictive control scheme for energy and cost savings in commercial buildings: An airport terminal building case study, Build. Environ. 89 (2015) 203–216.
[109] A. Kusiak, F. Tang, G. Xu, Multi-objective optimization of HVAC system with an evolutionary computation algorithm, Energy 36 (2011) 2440–2449.
[110] Y.M. Lee, R. Horesh, L. Liberti, Optimal HVAC control as demand response with on-site energy storage and generation system, Energy Procedia 78 (2015) 2106–2111.
[111] A.E. Ruano, S. Silva, S. Pesteh, P.M. Ferreira, H. Duarte, G. Mestre, H. Khosravani, R. Horta, Improving a neural networks based HVAC predictive control approach, in: 2015 IEEE 9th International Symposium on Intelligent Signal Processing (WISP) Proceedings, IEEE (2015) 1–6.
[112] D. Whitley, A.G.A. Tutorial, Statistics and Computing, 4, Kluwer AcademicPublishers. 4 (1994) 65–85.
[113] F. Bre, A.S. Silva, E. Ghisi, V.D. Fachinotti, Residential building design optimisation using sensitivity analysis and genetic algorithm, Energy Build. 133 (2016) 853–866.
[114] S. Carlucci, G. Cattarin, F. Causone, L. Pagliano, Multi-objective optimization of a nearly zero-energy building based on thermal and visual discomfort minimization using a non-dominated sorting genetic algorithm (NSGA-II), Energy Build. 104 (2015) 378–394.
[115] J.T. Jin, J.W. Jeong, Optimization of a free-form building shape to minimize external thermal load using genetic algorithm, Energy Build. 85 (2014) 473–482.
[116] V. Sambou, B. Lartigue, F. Monchoux, M. Adj, Thermal optimization of multilayered walls using genetic algorithms, Energy Build. 41 (2009) 1031–1036.
[117] X. Xu, S. Wang, Optimal simplified thermal models of building envelope based on frequency domain regression using genetic algorithm, Energy Build. 39 (2007) 525–536.
[118] A.M.A. Youssef, Z.J. Zhai, R.M. Reffat, Genetic algorithm based optimization for photovoltaics integrated building envelope, Energy Build. 127 (2016) 627–636.
[119] A. Zhang, R. Bokel, A. van den Dobbelsteen, Y. Sun, Q. Huang, Q. Zhang, Optimization of thermal and daylight performance of school buildings based on a multi-objective genetic algorithm in the cold climate of China, Energy Build. 139 (2017) 371–384.
[120] M. Hamdy, A.T. Nguyen, J.L.M. Hensen, A performance comparison of multi-objective optimization algorithms for solving nearly-zero-energy-building design problems, Energy Build. 121 (2016) 57–71.
[121] W. Yu, B. Li, H. Jia, M. Zhang, D. Wang, Application of multi-objective genetic algorithm to optimize energy efficiency and thermal comfort in building design, Energy Build. 88 (2015) 135–143.
[122] L. Magnier, F. Haghighat, Multiobjective optimization of building design using TRNSYS simulations, genetic algorithm, and Artificial Neural Network, Build. Environ. 45 (2010) 739–746.
[123] F. Hajabdollahi, Z. Hajabdollahi, H. Hajabdollahi, Thermo-economic modeling and optimization of underfloor heating using evolutionary algorithms, Energy Build. 47 (2012) 91–97.
[124] W. Huang, H.N. Lam, Using genetic algorithms to optimize controller parameters for HVAC systems, Energy Build. 26 (1997) 277–282.
[125] R.L. Navale, R.M. Nelson, Use of genetic algorithms and evolutionary strategies to develop an adaptive fuzzy logic controller for a cooling coil - Comparison of the AFLC with a standard PID controller, Energy Build. 45 (2012) 169–180.
[126] Y.C. Chang, J.K. Lin, M.H. Chuang, Optimal chiller loading by genetic algorithm for reducing energy consumption, Energy Build. 37 (2005) 147–155.

[127] R. Parameshwaran, R. Karunakaran, C.V.R. Kumar, S. Iniyan, Energy conservative building air conditioning system controlled and optimized using fuzzy-genetic algorithm, Energy Build. 42 (2010) 745–762.
[128] K. Li, W. Xue, C. Xu, H. Su, Optimization of ventilation system operation in office environment using POD model reduction and genetic algorithm, Energy Build. 67 (2013) 34–43.
[129] ASHRAE Standard 140-2017. Standard method of test for the evaluation of building energy analysis computer programs. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers. (2017).
[130] F.W.H. Yik, J.H.K. Lai, N.K. Fong, P.H.M. Leung, P.L. Yuen, A case study on the application of air- and water-cooled oil-free chillers to hospitals in Hong Kong, Build. Serv. Eng. Res. Technol. 33 (2012) 263–279.