Utrecht University

Biomimicry for a Sustainable Built Environment

A State-of-the-Art Review of Nature-Inspired Building Solutions

Pedram Keshmiri

MSc Bio-Inspired Innovation - Writing Assignment

Utrecht University (5092388)

Host organization: FiredUp Business Consulting

Examiner (UU): **Dr. Jaco Appelman**

Supervisor (host org.): **Bas Adib**

TABLE OF CONTENTS

DECLARATION OF COMMITMENT TO GSLS TERMS

The report has a single author, Pedram Keshmiri (5092388). Generative AI has been used for improving text flow and conciseness, according to Utrecht University's guidelines. The sources of all information (including figures, visuals or data) used in the report has been acknowledge and cited according to Utrecht University's guidelines.

SUMMARY

To reduce the environmental footprint of new buildings, architects and urban planners need to come up with innovative ideas. Nature can be a great source of innovative inspiration, as organisms in nature have evolved for billions of years to become climate adaptive, and to maintain a stable internal environment for their cells (aka homeostasis). While systems designed by humans are usually linear and have a single objective, natural systems consist of interconnected cycles that are regulated at different hierarchical levels and address multiple objectives. They do not produce waste either.

"Biomimicry" is an interdisciplinary field that addresses human problems by studying how nature works. It has the potential to make new buildings more in-sync with their environment. Essentially, when faced with a challenge, Biomimicry asks "how would nature approach this problem?" and "what does the surrounding ecosystem need from this building?". This approach can inspire creative, sustainable and even regenerative building design, if the designer has the right knowledge. For instance, at a basic level, buildings can adapt to their environment's temperature by regulating the sunlight that enters their façade, lowering the need for energy-intensive air conditioning. At a more advanced level, a building can emulate habitats on its façade for local plant and animal species.

In this review, thirteen projects are described where biomimicry has been integrated in building or façade design. Eight focus on regulating internal temperature and humidity (e.g., the Eastgate Center in Harare), while two projects focus on regulating air currents for energy efficiency and mechanical strength of high-rise buildings (e.g., The Gherkin in London). Three projects highlight the use of biomimicry for regulating water flows to support biodiversity (e.g., Marine Biomimetic Center in Biarritz), or to enable vegetable farming in dry areas of land (e.g., Sahara Forest Project). These cases demonstrate promising steps in applying biomimicry in architecture. Nevertheless, despite the potential, acceptance of projects that include biomimicry faces significant challenges. This is partly due to the lack of understanding among project owners and the scarcity of well-documented applied cases. Creating essential awareness among project owners, and more replicable examples (prototypes or final products) can improve clarity over the advantages, costs, and (long term) returns of a certain biomimetic approach. Additionally, the literature emphasizes the importance of cross-linking biology and engineering with a sustainability- and regeneration-focused mindset, going beyond simply mimicking natural forms. Establishing biomimetic design methods and developing educational programs are key to advancing this field.

ABSTRACT

In order to curb the substantial environmental footprint of new buildings, innovative approaches in architecture are needed. The new built environment needs to integrate with its surrounding environment rather than only becoming a burden on it. Nature presents the best model for designing efficient, renewable, and waste-free systems. While conventional human systems use excessive energy and resources, organisms leverage nested and interconnected systems, diversity and collaborative relationships to adapt to their environment. They also provide a steady internal environment (homeostasis), similar to what buildings aim to do for their residents (steady temperature, humidity). As such, nature's strategies can be a source of design inspiration for climate-adaptive architecture.

Biomimicry, an interdisciplinary approach to design and innovation, aims to solve human challenges by emulating nature's strategies that have evolved to be resource-efficient and sustainable. It also encourages designs that are in harmony with nature. Applying biomimicry in buildings is not a new concept, but it has gained traction in the past two decades. This study provides an overview of built or approved examples of biomimicry in the built environment in the 21st century, as described in scientific literature. Thirteen cases are described, and categorized into three groups based on their purpose: Heat and light regulation, air regulation, and water regulation. Regulating heat and solar is crucial for a more energy efficient interior climate control. Air regulation could be done to support the mechanical stability of buildings, as well as energy production to make them less reliant on the grid. Water regulation could enable vegetable farming in arid areas, or provide a basis for habitats in and around buildings.

The cases showcase promising initial steps in the application of biomimetic design in the built environment, while also highlighting the essential need for strengthening the interdisciplinary links between biology and (urban) architecture.

.

1. INTRODUCTION

1.1 THE FOOTPRINT OF BUILDINGS

Most human urban settlements rely on fossil fuels for heating, food production, and transportation, operating in a linear system that contributes to pollution and climate change. This approach also degrades water sources, air quality, soil, and human health, while depleting non-renewable resources in unsustainable ways (Pedersen Zari & Hecht, 2020).

Globally, the built environment accounts for 40 % of energy-related GHGs and roughly 33 % of total energy demand (World Business Council for Sustainable Development, 2023). The term "built environment" encompasses design, construction, management and use of buildings, thus includes activities such as heating, cooling, lighting and using electrical devices. In the EU, the built environment is responsible for 35 % of energy-related greenhouse gas emissions and 42 % of total energy demand. Only a fourth of this energy used for heating and cooling in the EU came from renewable sources (European Environment Agency, 2023; Eurostat, 2024; Teixeira, 2021; TNO, 2023a). Moreover, when looking at household energy consumption, heating homes accounted for 63.5 % of the total residential energy consumption (European Environmental Agency, 2022). In the Netherlands, the built environment is responsible for a 33 – 38 % of GHG emissions and about 30 - 37 % of the nation's energy use (Dutch Green Building Council, 2021; Energie in Nederland, 2021; TNO, 2023b). Furthermore, it accounts for 50% of the nation's total material consumption, and generation of roughly 40 % of the country's total waste (~ 25 million tons of Construction and Demolition Waste (CDW) annually) (Circle Economy Foundation, 2024).

Many concrete structures constructed in the post-World War II era in Europe, particularly from the 1950s, are now nearing the end of their lifespan and soon need to be renovated or rebuilt. This represents an opportunity for innovation in designing more energy and material efficient buildings. In the Netherlands, the government has committed to making the built environment carbon neutral by 2050 (Hoogenboom, 2023; Yu et al., 2021). Furthermore, new initiatives are needed to boost urban biodiversity in Europe. This is not typically prioritized in architectural design, pushing nature conservation efforts to focus on the limited space which is free of buildings, and overlooking the potential of the built environment (European Parliament, 2023). Buildings can be designed for both human and non-human inhabitants, offering people greater opportunities to benefit from their connection to nature (Weisser et al., 2022).

The term "Biophilia," derived from the Ancient Greek words *bio* (life) and *philia* (love), reflects the inherent human affinity for nature. It underscores the deep psychological connection between people and natural systems. Similarly, biophilic design incorporates elements of the natural world—such as plants or animals—into building interiors and exteriors, enhancing urban spaces and fostering a sense of belonging and well-being (AlAli et al., 2023). Integrating biological forms, functions and strategies into the built environment can offer the inherent benefits of natural ecosystems, such as rainwater harvesting, flood mitigation, habitat creation, energy production and carbon sequestration. In doing so, human-populated environments can "fit in" in to the ecosystems they inhabit (Phillips, 2015).

Furthermore, nature presents the best model for designing efficient, renewable, and waste-free systems (G. Oliveira, 2023). While conventional human systems tend to use excessive energy and resources to fight the surrounding climate, natural systems embody resilience by adapting to climate challenges. They do so by leveraging locally available resources, diversity, and cyclic, interconnected processes that achieve multiple purposes. These strategies can be a source of design inspiration for climate-adaptive architecture (Phillips, 2015).

1.2 WHAT IS BIOMIMICRY?

Biomimicry is defined by ISO as “the philosophy and interdisciplinary design approaches taking nature as a model to meet the challenges of sustainable development, including social, environmental, and economic”. It is an interdisciplinary approach with significant potential for sustainable development and applicable in different sectors such as architecture, engineering, material science and so on (ISO, 2023). When designing a built environment, integrating biomimicry can disrupt conventional thinking methods. Asking “how would nature approach this problem?” can boost creative ideas, if the designer is equipped with the knowledge or the tools to acquire it (Phillips, 2015).

Biomimicry can be understood and applied at three levels: organism (imitating part or all of an animal or plant), behavior (replicating the actions or interactions of an organism with its environment), and ecosystem (studying the broader interactions and functions within a system). Each level can also be explored through various dimensions, including form, material composition, construction, and functions (AlAli et al., 2023). Mimicking an organism in isolation, without considering how it interacts within its ecosystem, can lead to designs that lack environmental benefits (Reap et al., 2005). For instance, merely copying the shape of a cactus for a building design (simple biomorphism) may not enhance its sustainability performance. Behavior-level biomimicry, on the other hand, involves replicating the organism’s actions. Here, designers must assess whether the organism's behavior is appropriate for human application and determine which aspects could contribute to the building's sustainability (Mirniazmandan & Rahimianzarif, 2017).

Biomimicry distinguishes itself from other forms of bioinspiration (figure 1). It aims to holistically learn from nature’s form, function, and systems with the purpose of coming up with sustainable (and ideally regenerative) solutions. On the contrary, Biophilia merely focuses on natural aesthetics or symbolic purposes (Learn Biomimicry, 2024). Biomimicry also differs from biophilia, biomorphism, bio utilization and bionics: Biomorphism focuses on incorporating natural shapes and aesthetics from biology into art, design, or architecture, emphasizing visual aspects rather than functionality. Bio-utilization refers to the direct use of biological organisms or materials without imitating their natural functions, while Biophysics studies the mechanical structure, function, and movement of biological systems. Bionics applies knowledge of biological systems to solve engineering problems. It focuses on using biological insights to inspire solutions rather than directly replicating nature's designs (Sorensen, 2024).

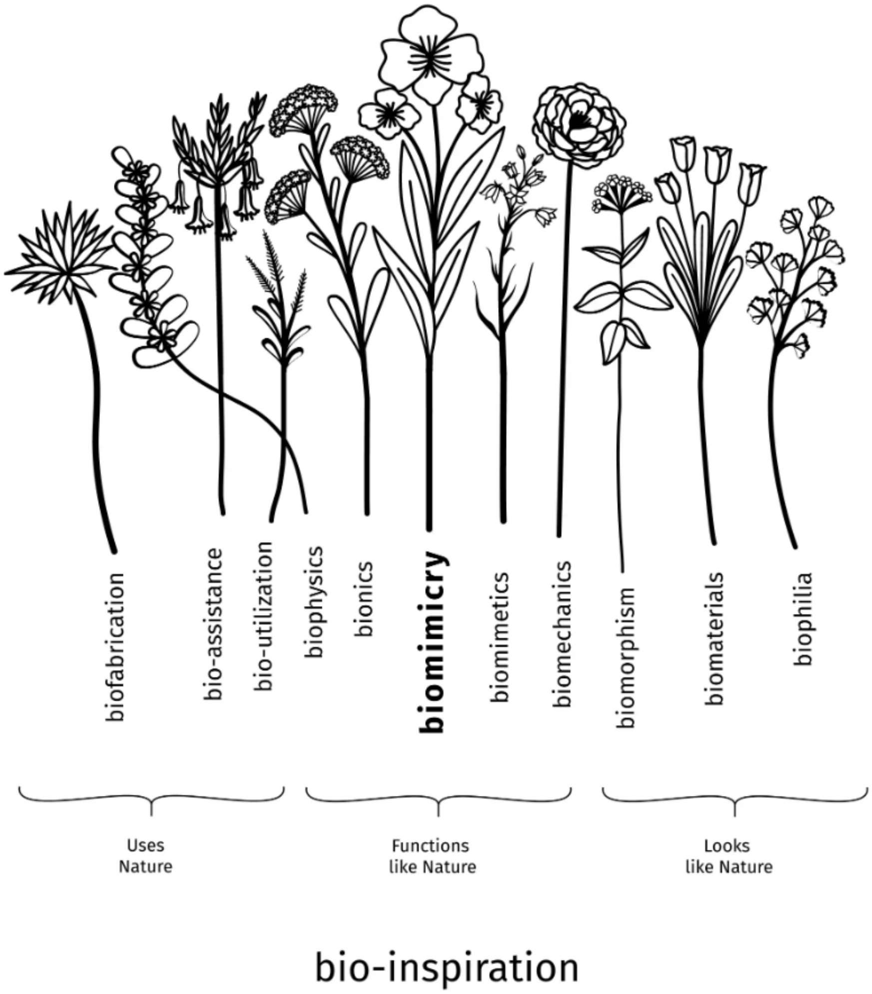


Figure 1 - Various forms of bioinspiration. This figure aims to distinguish between bio utilization approaches which use natural systems to gain benefits for humans (left side), various forms of mimicking natural forms such as biomorphism (right side) Biomimicry is a holistic approach which aims to beyond merely aesthetics or utilization, by emulating the functions of natural systems and or utilization, by learning from the functions of natural systems to come up with durable solutions. Figure retrieved from (Learn Biomimicry, 2024).

Application of biomimicry can be carried out in a top-down or bottom-up approach. The top-down approach, which is also known as "technology pull" means design is looking to biology. It begins with identifying design problems and is followed by searching in biological strategies before coming up with implementable solutions. The bottom-up approach, or "biology push", starts with biological research and modeling before finding technical applications and design solutions.

Nature's six main design principles (table 1A in appendix A) can serve as a useful measuring and evaluation tool for biomimicry in architectural projects. Other credible and established frameworks for evaluating designs are scarce, but becoming increasingly available (e.g. the Living Building Challenge (LBC) (Living Future Institute, 2024)).

1.3 WHY BIOMIMICRY FOR SUSTAINABLE BUILDINGS?

Nature designs multi-purpose systems which can achieve multiple goals, while humans typically use one strategy for one problem. For instance, wrinkles on skin serve multiple functions in nature: (1) increasing surface area for moisture retention; (2) aiding evaporation; and (3) providing shade. This biological feature can influence and regulate all four environmental factors (Badarnah, 2017). As such, a single biological strategy can be emulated for addressing multiple design goals in the built environment. In fact, in many ways, a "Building" resembles a "Plant". They are both static structures which need to be tolerant towards their external environment. They also both need to regulate their internal temperature and humidity; one for survival, and the other for creating comfort for its users (Sommese et al., 2022). Buildings can also be thought of as nested systems, on the one hand being made up of smaller systems and on the other hand, being part of an enclosed larger system. Seen as such, collaborative relationships can be developed at different levels of these systems to save energy and costs (Phillips, 2015). Applying biomimicry in architectural design requires knowledge and thoughtful iterations, evaluation and refinement; if it aims to go beyond mere biomorphism (G. Oliveira, 2023). For an effective integration, the engagement of biologists, architects, and engineers in the design phase may be required (Phillips, 2015).

Beyond the individual building level, biomimicry can revolutionize entire cities by acting as a source of innovation for projects that reconnect the urban space to natural ecosystems and regenerate whole socio-ecosystems. With new urban design and planning approaches increasingly focusing on regenerative design, ecosystem-level biomimicry, and ecosystem services theories, nature-inspired strategies can be used for designing urban environments that mimic natural ecosystems and lead to healthier, more livable urban spaces (Blanco et al., 2021; G. Oliveira, 2023; Pedersen Zari & Hecht, 2020).

1.4 SCOPE

This study aims to provide an overview of built or approved examples of biomimicry in the built environment (top-down approach) in the 21st century, which are described in scientific literature. Of the thirteen projects described, eleven have completed their construction phase and are already in use, while two still in development. Halted or cancelled projects are not included. Rejected proposals were also considered out of scope.

The cases are divided into 3 subgroups based on the primary purpose of biomimicry integration. First category addresses "heat and light" regulation for thermal and visual comfort. This is the group with the most cases (8). Second category focuses on air regulation for purposes other than thermal comfort, for instance increasing mechanical resistance or reducing material consumption. The third category focuses on biodiversity hosting and indoor farming.

2. METHODOLOGY

For this literature review, studies published in English on Utrecht university online library (Worldcat), Google scholar, PubMed and Scopus were analyzed. Additionally, non-academic sources such as (local) government websites, company websites, newspapers, and blog posts were used. The following is an overview of the search terms used. If a search term has a phrase in parentheses () it means the term has been queried with and without that phrase. The terms sometimes delivered overlapping results.

Search terms:

To find case studies:

- Biomimicry in the built environment (state of the art)
- Biomimicry built environment (case studies)
- State of the art biomimicry built environment (Europe)
- Biomimicry in architecture (state of the art)
- Biomimicry in architecture (case studies)
- Biomimicry urban architecture case study
- Biomimicry in buildings case studies (Europe/Netherlands/France/Germany)
- Most prominent biomimicry cases in architecture
- Biomimicry in buildings (case studies)
- Biomimicry in construction
- Adaptive façade biomimicry (case studies)
- Building envelope biomimicry (case studies)
- HVAC biomimicry case studies
- Thermal regulation architecture biomimicry
- Thermal regulation architecture biomimicry case studies
- Biomimicry for biodiversity (hosting/support) in architecture (case studies)
- Biomimicry for biodiversity (hosting/support) in built environment (case studies)

Specific case descriptions, biological models and innovations:

- Eastgate center Harare biomimicry
    - Termite mounds
    - Termite mounds air circulation system
    - Clay properties termite mound
    - Clay characteristics sustainable construction
    - Clay brick end of life cycle (possibilities)
- The council house 2 Melbourne Biomimicry
    - Phase change materials
- Nianing church Senegal biomimicry
- The one ocean building South Korea biomimicry
    - Flectofin system (biomimicry)

  - Bird of paradise flower (mechanism)
  - *Strelitzia reginae* flower (mechanism)
  - Glass-fiber reinforced polymer (GFRP)
  - lateral torsional buckling (LTB)
- The Tyssenkrupp Q1 building biomimicry
  - Fins opening mechanism
- Esplanade theatre Singapore biomimicry
  - Durian fruit
- Hygroskin pavilion Orleans biomimicry
  - Hygromorphic qualities of wood
  - Hygroscopic actuation plants
  - Pine cone hygroscopic functions
  - Pine cone response to rain mechanism
- Pho'liage France biomimicry
- Pho'liage shading system biomimicry
  - Plant leaves opening mechanism
  - Nyctinastic plant movements
  - Thermostatic bimetals
  - International agency for research on cancer France (biomimicry)
- Pearl river building Guangzhou biomimicry
  - Sea sponge
  - Venus flower basket glass sponge (biomimicry)
  - *Euplectella aspergillum* (biomimicry)
  - Venus flower basket sponge (water) filtration mechanism
- The Gherkin tower London
- The Swiss Re building London
  - Diagrid exoskeleton structure (The Gherkin)
  - Glass sponge filtration mechanism
  - Hexactinellid sponge
  - *Euplectella aspergillum*
- The Sahara forest project biomimicry
  - Sahara forest project irrigation mechanism
  - Namib desert beetle (fog harvesting mechanism)
- Marine biomimetic center in Biarritz biomimicry
  - Project ESTRAN (biomimicry)
  - ESTRAN project biodiversity
  - Foreshore ecosystem
  - Intertidal zone ecosystem
  - Supralittoral
  - Intertidal
  - Sublittoral
  - ESTRAN project rain harvesting mechanism

    - Biarritz local ecosystem (characteristics)
- The Eden project biomimicry
    - Ethylene tetrafluoroethylene (ETFE)
    - Geodesic structural frames
    - Mediterranean habitat (temperature and humidity)
    - Tropical habitat (temperature and humidity)

To better understand the state of the art, the focus was laid on literature published after 2015. Furthermore, more focus was laid on cases in Europe or climates comparable to Europe.

The cases were chosen only if the integration of biomimicry improved at least one aspect of the building or structure's environmental sustainability performance as indicated in scientific literature; namely energy efficiency, use of renewable energy, water use, waste generation and processing, use of (low-footprint) raw materials, and biodiversity support (Ali & Al Nsairat, 2009; Bragança et al., 2010; Zulkefli et al., 2022). Thirteen projects are described in this review, eleven of which had completed their construction phase and are already in use, while two are still in development. Halted and cancelled projects as well as rejected proposals are not included.

Since the initial queries to find cases were mainly done in English, this work is limited to studies published in this language. While sometimes identified cases were investigated in other languages with the help of google translate, it may be that smaller scale, local, less internationally recognized cases of biomimicry in the built environment may have been overlooked.

3. THE CASES

3.1. HEAT & LIGHT REGULATION: THERMAL AND VISUAL COMFORT

1. The Eastgate Center (EC) in Harare, Zimbabwe

Designed by Mick Pearce, the EC is an office building combined with a shopping center which opened its doors in 1996. Its ventilation and cooling system is inspired by African termite mounds, and it is one of the most cited cases of biomimicry in architecture. Pearce wanted to avoid a glass block design which would be typically expensive to maintain at a comfortable temperature. So he chose an alternative approach, one that was based on adaptation to the regional climate and biosphere and the local human resources. The EC features two office buildings connected by a glass roof, with chimneys that extract warm air from the floors below. Fans pull cool air from the central atrium into the offices, while heated air is directed into internal cavities. This system enables night cooling, thermal storage, and convective air circulation, all similar to the function of termite mounds, reducing energy consumption by 50 %. It also successfully maintains comfortable temperatures for all but 2 weeks in a year (Verbrugghe et al., 2023). The building is constructed with clay bricks, similar to termite nests. As a construction material, clay offers durability, strength, thermal and sound insulation, moisture retention and fire resistance properties (Shubbar et al., 2019). While their production can require high levels of energy depending on drying (burning) method, the durability of clay bricks (up to 100 years) can potentially offset some of these emissions. Additionally, clay waste from construction and used clay bricks (end of life cycle) can be reused in renovation projects or recycled for use in new construction. by crushing to make recycled bricks (Hernández García et al., 2024; Oberst et al., 2016).

Mound-building termites create large, vertical mounds using soil, saliva, and excrements, with some African mounds reaching up to 8 meters. During the day, these mounds warm up in the sun and at night, the warmer internal air rises and exits from the top through chimney-like structures, pulling in cooler outside air into the bottom of the mound through tunnels, keeping the nests at a stable temperature. The complex network of tunnels in mounds is known as the "egress complex," which regulates temperature and airflow. These intricate network is dug by worker termites and the colony—living in underground nests—can house up to a million termites. Depending on the species, some mounds have open chimneys or vent holes, while others have porous walls but no large openings. The egress complex enhances ventilation by using wind-driven turbulence to support gas exchange and moisture control. While details are still unclear, it seems that the main process involves air currents created by solar heat. As the sun heats different parts of the mound throughout the day, temperature differences cause air to rise and fall, promoting airflow inside. The soil acts as a thermal buffer, absorbing and releasing heat to stabilize the nest's environment. New research on species like *Macrotermes michaelseni* suggests that termite mounds function like mammalian lungs, aiding gas exchange in underground nests. The cool air is drawn in at the base, while warm air rises and exits through vents. During the rainy season, termites open tunnels to manage moisture and airflow (Ask Nature, 2020; Dijkstra, 2023). As such, termite mounds are more than just a nest for living. Their optimized location, materials and structure are not only adapted to its local ecosystem, but also benefit the local environment through recycling organic material (particularly phosphorus) and improving soil quality (López-Hernández, 2023).

Inspired by termite mounds, the EC uses chimney-like structures to vent warm air, while cool night air is stored underground and released during the day (figure 5, left). To complement this, the cool air enters each office room from vents at the bottom (figure 5, right). As the air warms up due to human activity, it gradually rises and exits through vents at the top, reducing the need for air conditioning. In addition to termite mounds, Pearce also took inspiration from cacti, which have a lot of wrinkles, spikes, and ridges to increase surface temperature and disperse heat. Similarly, the EC's façade uses many protruding stone and concrete shapes and projections, as well as deep balconies and plants for heat dispersion and shading over windows. Both of these strategies support the EC to achieve comfortable internal temperatures without using air conditioning (Pearce, 2016b).

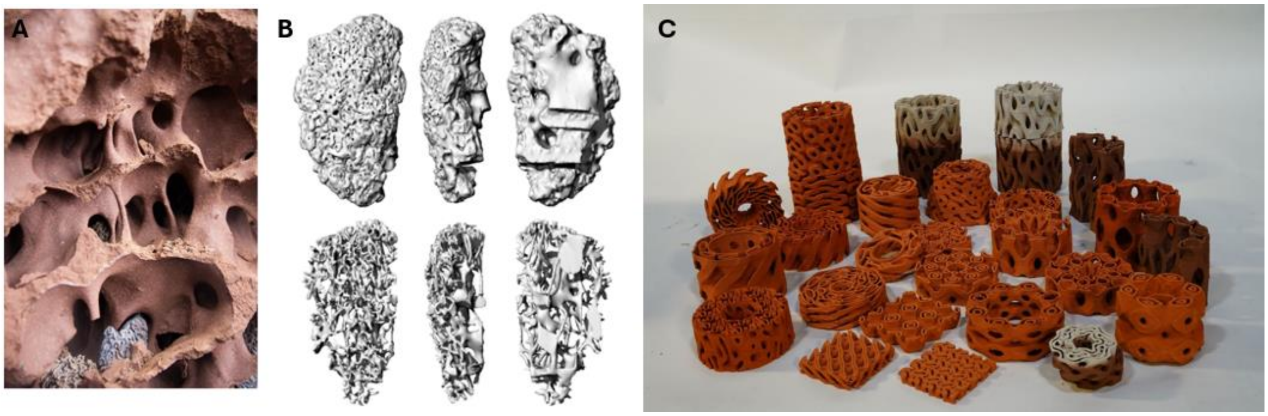


Figure 2 – A and B: : Interior structure of termite-made mounds. Fragment of the egress complex of Macrotermes michaelseni. Using a 3D model of the complex (B), researchers found that airflow varies at different oscillation frequencies, with the strongest at 30-40 Hz (Dijkstra, 2023). Once fully understood, these structures could inspire 3D-printed building materials for façade panels or walls which enable temperature and moisture regulation through evaporative cooling and improved air flow, reducing the input of conventional air conditioning systems. C: Prototypes of 3D printed clay materials for exterior and interior, an artistic emulation of the egress complex (Torres, 2024).

Figure 3 - EC building in Harare, Zimbabwe. The façade of the building is designed with deep balconies, and protruding stone and concrete shapes as and plants for heat dispersion and shading over the windows. EC's prickly or textured surfaces aren't efficient at collecting heat during the day, and they excel at emitting heat at night, thus cooling down the building for the next day. In contrast, smooth surfaces such as glass building envelopes would absorb more heat at night while radiating less back into space.

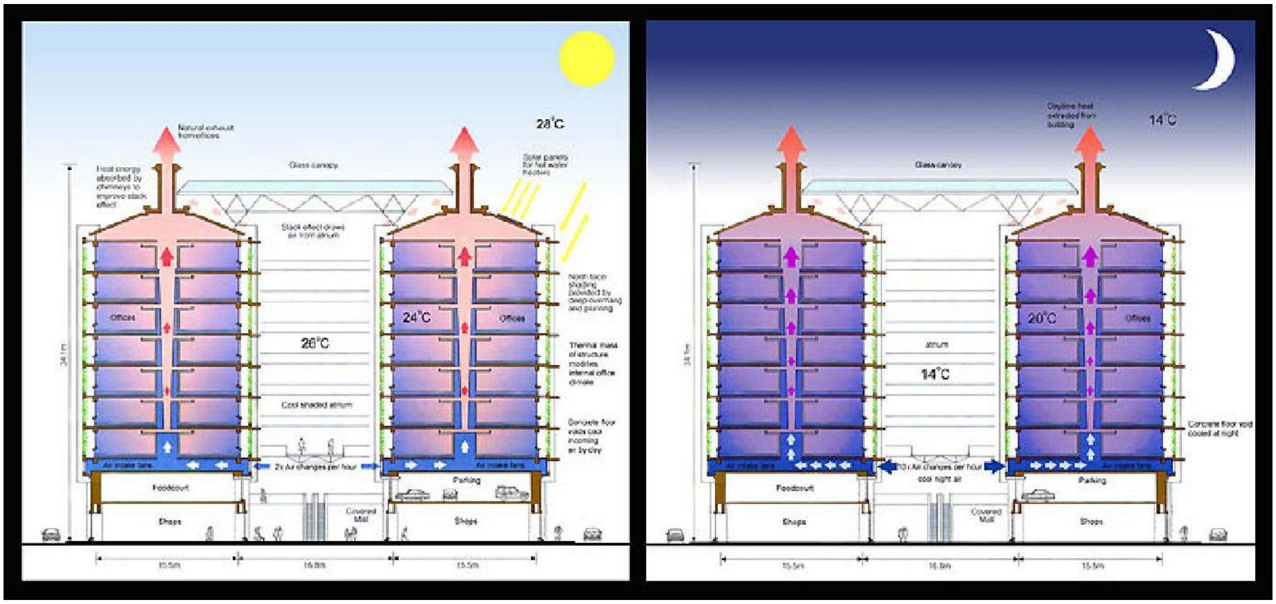


Figure 4 - The climate control system of EC uses chimney-like structures to vent warm air out during the day, while cool night air is stored underground and released during the next day from the atrium, reducing the need for air conditioning. Figure retrieved from (Pearce, 2016b).

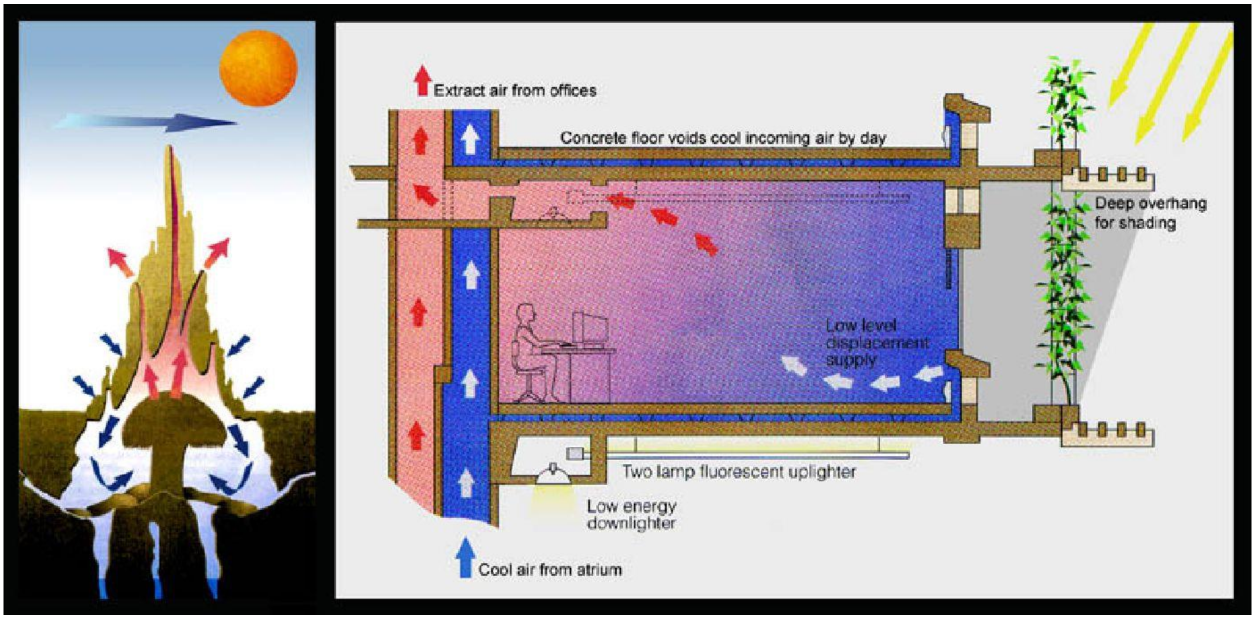


Figure 5 – Left: air circulation through a termite mound. Cool air is drawn in at the bottom and further cooled using moisture, while warm air exits through the vents on top. Right: Air flows from the ducts through hollow floors to low-level grilles under windows. It then rises as it warms from human activity, reaching the vaulted ceiling where it is drawn out through exhaust ports. This air is then channeled to the central exhaust stacks. In the office space, uplighters reflect light downward from the concrete vaulted ceiling, which also absorbs heat. Figure retrieved from (Pearce, 2016b)

Figure 6 - Temperature measurements using data loggers in the EC, two years after it opened its doors. The internal temperature tends to stay within the comfortable range of 20 - 25 °C. The peak internal temperatures were recorded at 27 – 28 °C, at around 4 pm, on a number of days within a two – three week period. During the day, people and machines raise the internal temperature by 1.5°C, which can accumulate over the workweek if not released during the night, causing a buildup until the weekend when the building cools sufficiently. Figure retrieved from (Pearce, 2016b).

2. The Council House 2 (CH2) in Melbourne city, Australia

The CH2, officially opened in August 2006, is a 10-level building that houses the Municipal offices of Melbourne city in Australia. At the time of its construction, it was the first six-star rated green building in Australia. The CH2 utilizes passive climate control systems based on the principles seen in termite mounds (figure 2 A and B).

Biomimicry is used throughout the building, with each facade representing different aspects of a tree. The west façade mimics tree epidermis, helping to moderate external climate, while the north and south facades are like tree bronchi, acting as wind pipes with exterior air ducts. The eastern core, resembling tree bark, provides a protective layer that filters light and air into ventilated spaces. Perforated metal and polycarbonate walls on overlapping facade layers support the louvered structure (Radwan & Osama, 2016). CH2's prominent facade features hydraulically-adjustable timber slats which cover a glass wall. These slats move to adapt to sunlight and time of day, making them a responsive element. Additionally, six large, yellow wind turbines on the building's roof help capture and utilize wind energy and also use wind to ventilate the building's interior. Stale air is purged at night through hollow floors towards ventilation shafts and eventually through roof vents. Fresh air is pulled in during the day through the automatic shutters.

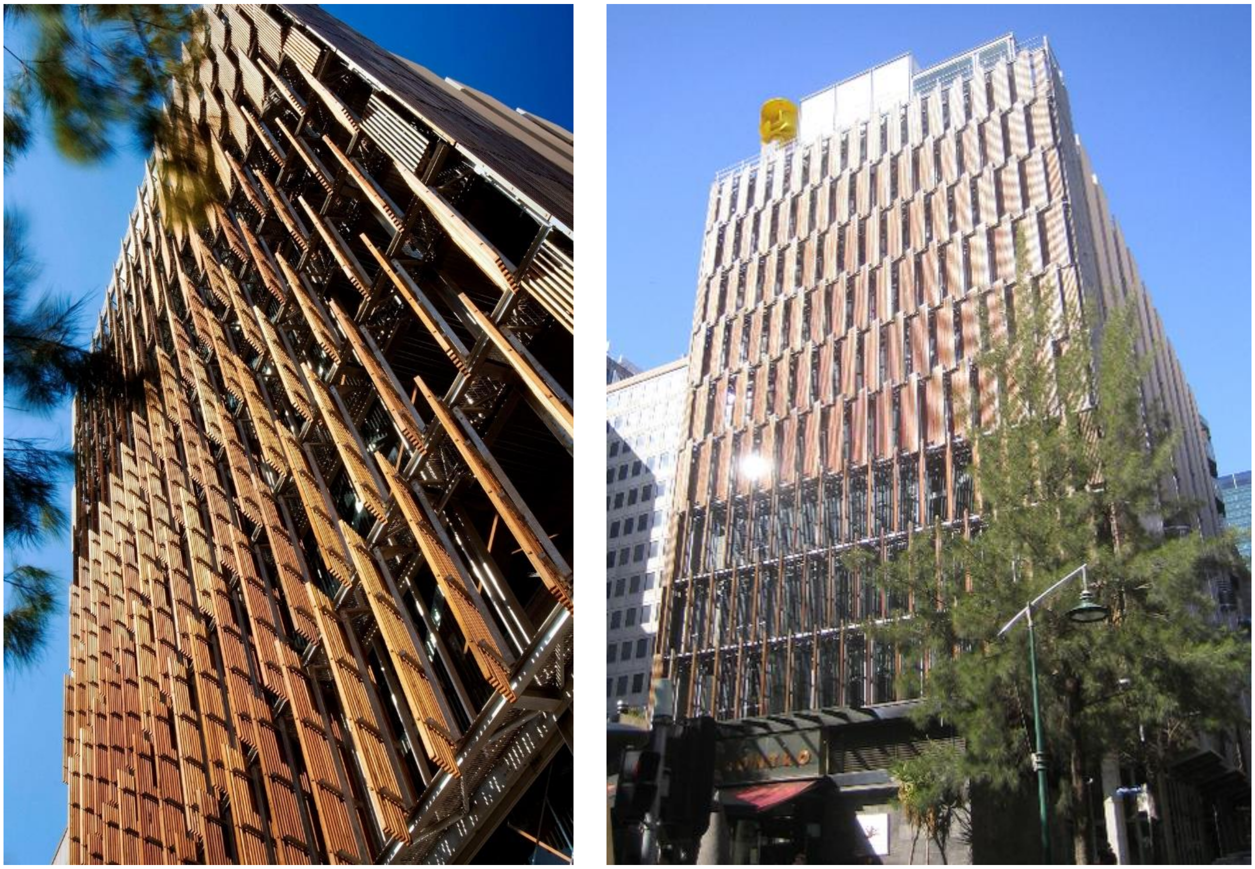


Figure 7 - The exterior façade of CH2 is composed of wooden slates made from recycled timber, which adapt to the angle and intensity of sunlight to regulate indoor temperature and lighting.

CH2 was aimed at being almost carbon-neutral. It is constructed almost entirely with recycled and renewable materials, for instance its outer façade is made of recycled timber. It also uses natural convection, ventilation stacks, thermal mass, phase change materials, and water for cooling. Another bio-inspired feature is the building's skin system. The 'dermis' includes the outer zone for stairs, lifts, ducts, balconies, and sunscreens, constructed with a lightweight steel frame. The 'epidermis' provides sun and glare control, creating a semi-enclosed micro-environment. The pre-cast concrete ceilings have a wavy design to increase surface area and boost thermal mass. At night, a night purge cools the thermal mass with outside air, allowing it to absorb heat during the day (Verbrugghe et al., 2023).

Natural daylighting in CH2 was challenging due to its orientation, surrounding buildings, and the need for a deep open-plan office. To maximize natural light, the design used a combination of window size, air ducts, light shelves, vaulted ceilings, shading, and timber louvres. Light shelves on the north façade reflect soft light onto the ceiling and are made of fabric in a steel frame. Vaulted ceilings allow deeper light penetration, and windows at the highest point enhance this effect. The east façade uses perforated metal for shading and natural ventilation, while the north has vertical gardens to reduce glare (Verbrugghe et al., 2023).

Furthermore, CH2 employs closed loop resource systems by for instance having an in house water treatment system. It can even use the city sewage to produce water, by means of a 3-layer filtering system. This water is then used for conditioning the air. The air conditioning water is directed down the exterior of the building through five 15 meter - "shower towers" (Pearce, 2016a). This process generates evaporatively cooled air, which is then introduced into the lower commercial spaces (figure 8). The remaining amount of filtered water is stored and cooled using Phase Change Materials and will later be used for flushing the toilets and watering the plants (Pearce, 2016a).

The payback period for the additional investments made on the building's sustainable features was estimated to be around 10 years, excluding the positive impact on employee performance estimated to be $2 million (Australian) a year (Pearce, 2016a). Nonetheless, a study in 2013 demonstrated that its actual energy performance is closer to 4 stars, so better than average but below its potential (Verbrugghe et al., 2023)..

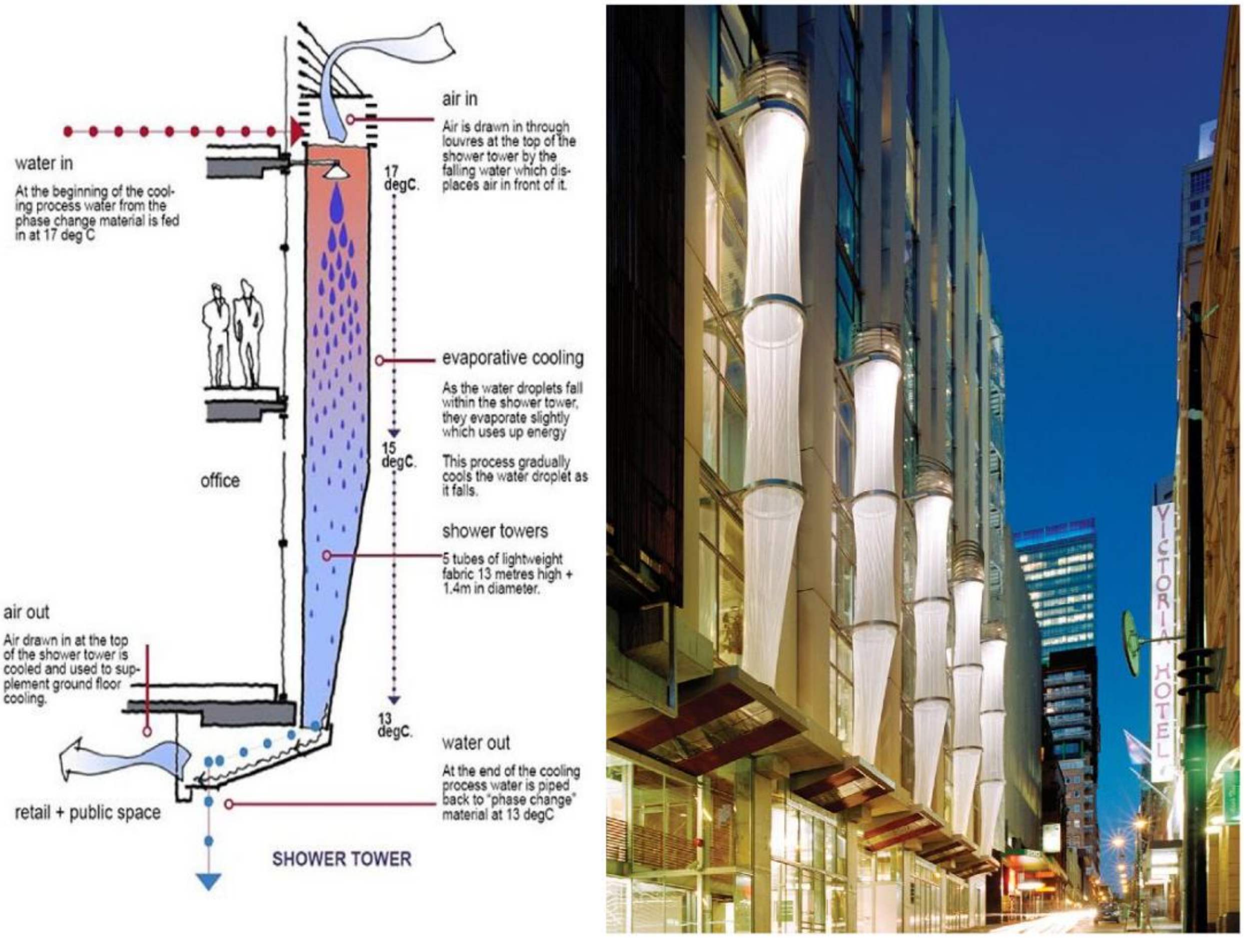


Figure 8 - The shower towers of CH2 capture air from their top side and condition it with water droplets to produce cool air for ventilating the interior spaces of the building. Figure retrieved from (Pearce, 2016a).

Phase Change Materials (PCMs) used in CH2 to cool the water are a passive temperature regulation solution for buildings, which lower heating loads at night, thereby stabilizing temperature fluctuations to save energy. They can be implemented as bricks in walls or roofs or as standalone thermal storage units. PCM integration also increases the thermal capacity of walls and roofs, thereby lowering heat transfer and limiting temperature spikes by moderating temperature variations during warm summer days. Experimental tests show that they decrease heat transfer by 40 – 60 % (Saxena et al., 2020). PCMs effectively act as a heat storage "battery", storing and releasing thermal energy at specific temperatures during state changes (e.g., from solid to liquid). This heat which is used during a state change of a material is known as "latent" heat. PCMs typically have high latent heat capacities, making them more effective than conventional materials for thermal energy storage. They are categorized into three groups: organic (like paraffins), inorganic (like hydrated salts), and eutectic mixtures. Each type has distinct properties suitable for specific applications. Choosing the right PCM involves considering thermodynamic, kinetic, and chemical features for the desired environmental and building conditions. In colder climates such as the Netherlands or Canada, PCMs can reduce the heating loads by 30 %, and the yearly heating requirements by 17 % (Entrop et al., 2016; Guarino et al., 2017; Saxena et al., 2020).

According to the research by (Entrop et al., 2016), most PCMs for regulating indoor temperature have a melting temperature in the range of 20 - 25 °C (thus around the comfort temperature). As a result, in the Dutch climate, they could be properly charged only around 50 – 80 days per year, when the outside temperatures exceed their melting points. This means that developing PCMs with lower melting temperatures closer to the modal temperatures in the Netherlands could increase their efficacy in buildings, as they would keep the temperature above a certain limit, lowering the energy required (for instance, by electric heating systems) for bringing it to the comfortable range of 20 – 25 °C. Additionally, the reliability of PCMs in concrete can also be improved. Despite manufacturer claims, mixing concrete can damage some PCM micro-capsules, leading to leakage of paraffin wax, which may evaporate over time. This leakage reduces the material's heat storage capacity, potentially lowering its effectiveness for temperature regulation (Entrop et al., 2016).

3. Nianing church in Nianing, Senegal

This church is located in Nianing, around 100 km away from Dakar, on what is called the “shell coast”. It takes inspiration from the shape of a spiral shell, and is architecturally developed based on the specific characteristic of its bioclimatic positioning. It is a unique example of a cultural biomimetic architecture which has won the global design awards for in-situ architecture in 2019 (Rethinking The Future, 2019). The Nianing church utilizes passive thermal regulation inspired by termite mounds (figures 2 and 5), which were also seen in CH2 and Eastgate center Harare (Blanco, Cruz, et al., 2021). On its northern site, the church closes off to shield itself from the hot, dry Harmattan winds, while opening towards the west to embrace the cooling trade winds from the sea. The bell tower acts as a "wind tower," utilizing natural convection to draw in the trade winds and facilitate natural ventilation throughout the building (Rethinking The Future, 2019).

Figure 9 - The Nianing church’s design resembles a spiral shell. Figure retrieved from (Blanco, Cruz, et al., 2021).

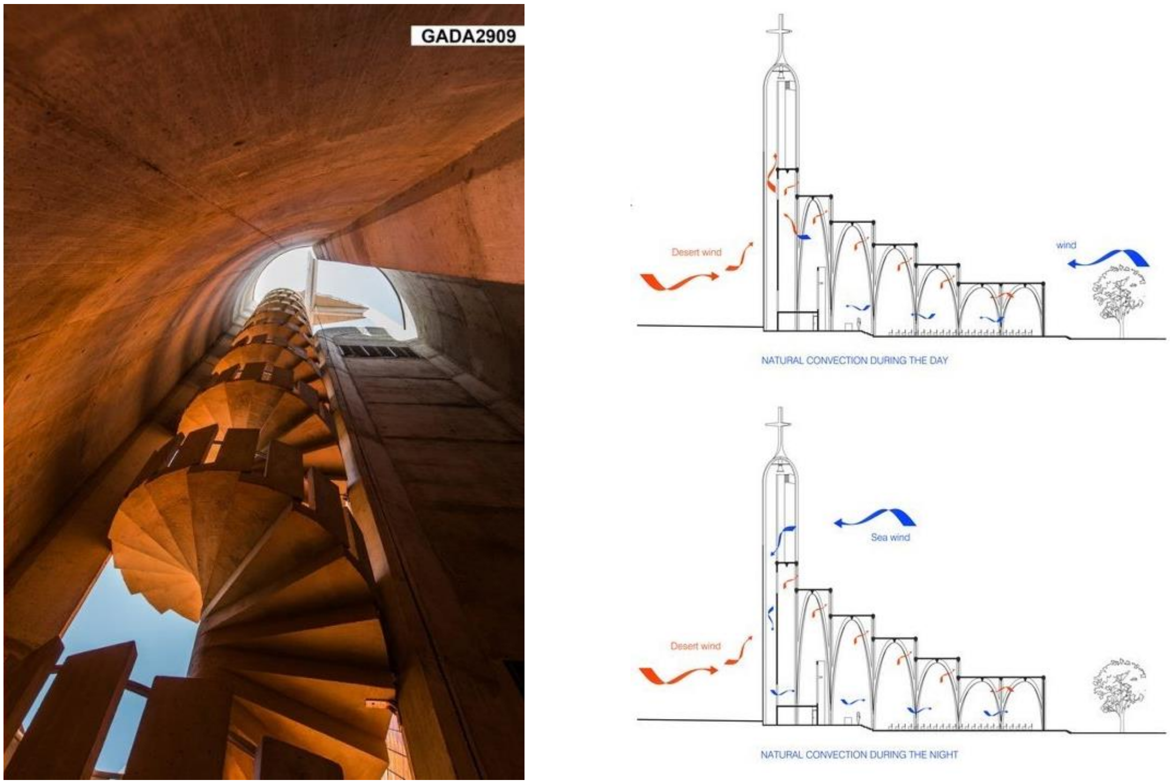


Figure 10 - The wind tower of Nianing church (left), The bell tower functions as a wind tower which brings in cool air from the side of the sea, facilitating natural ventilation (right). Figure retrieved from (Rethinking The Future, 2019).

Figure 11 - Nianing church from different angles (Rethinking The Future, 2019).

4. The One Ocean (OOB), a thematic pavilion in Yeosu, South Korea

The OOB is a permanent structure which was built for the 2012 expo “The Living Ocean and Coast” in South Korea (figure 12). It has viewing platforms and roof gardens with local plant varieties. It was designed by the Austria-based Soma architecture. The OOB features a kinetic façade which regulates the interior light during the day by moving its lamellae (figure 14) that create wave-like patterns. Light can come in and out, or the structure can close up entirely (Srishti, 2021).

The OOB’s *Lamellae* are made of glass fiber reinforced polymers (GFRP) which can be molded into various dynamic-looking designs. They use the Flectofin™ system for dynamic light control, developed by the Institute of Building Structures and Structural Design (ITKE), at the University of Stuttgart (Verbrugghe et al., 2023). The Flectofin™ is a patented, hingeless flapping device which is inspired by the pollination mechanism of the bird-of-paradise flower (*Strelitzia reginae*), and uses fiber-reinforced polymers like GFRP to achieve high tensile strength while remaining flexible. It uses sensors and actuators, but no hinges: Traditionally, the actuator systems deployed in architecture rely on hinges and rollers which are maintenance-heavy. The designers were tasked to come up with an actuator system that requires less maintenance, which is when they looked into previous research on plants, particularly the ones that rely on elastic deformations instead of rollers and hinges. The bird of paradise flower’s pollination mechanism used ‘external actuation’ through a special form of lateral torsional buckling (LTB) (figure 13). In this flower, external actuation refers to the movement of two adnate petals forming a perch for birds. When birds land to access nectar, the pressure on the perch bends these petals, revealing the flower’s pollen. In this moment, while the flower is simultaneously under bending and torsion, the pollen attach to the birds' feet, aiding pollination. Once the bird leaves, the perch returns to its original closed position. In architecture however, LTB is known as a failure mode that occurs in beams when they are subjected to bending, particularly when the compression side tries to buckle sideways and twist. Looking at the bird of paradise flower, they discovered that attaching a thin shell element to a rib enabled a distinct form of LTB. They then studied suitable materials for technical applications. The Flectofin™ shading system, which functions without hinges, features vertical backbones with laminae attached to each. Raising or lowering the support structure bends the backbones, causing the lamellae to open or close (Salgueiredo & Hatchuel, 2016). This enables the creation of complex, kinetic forms called pliable structures, like the one used in OOB (Lienhard et al., 2011; Uchiyama et al., 2020). The number of panels used in the Flectofin™ system can be increased to cover larger areas in a façade shading system, making this innovation scalable (Masselter et al., 2012; Sommese et al., 2022).

Figure 12 - The OOB's horizontal spatial design is inspired by the vast "never-ending" surface of the ocean (biomorphism).

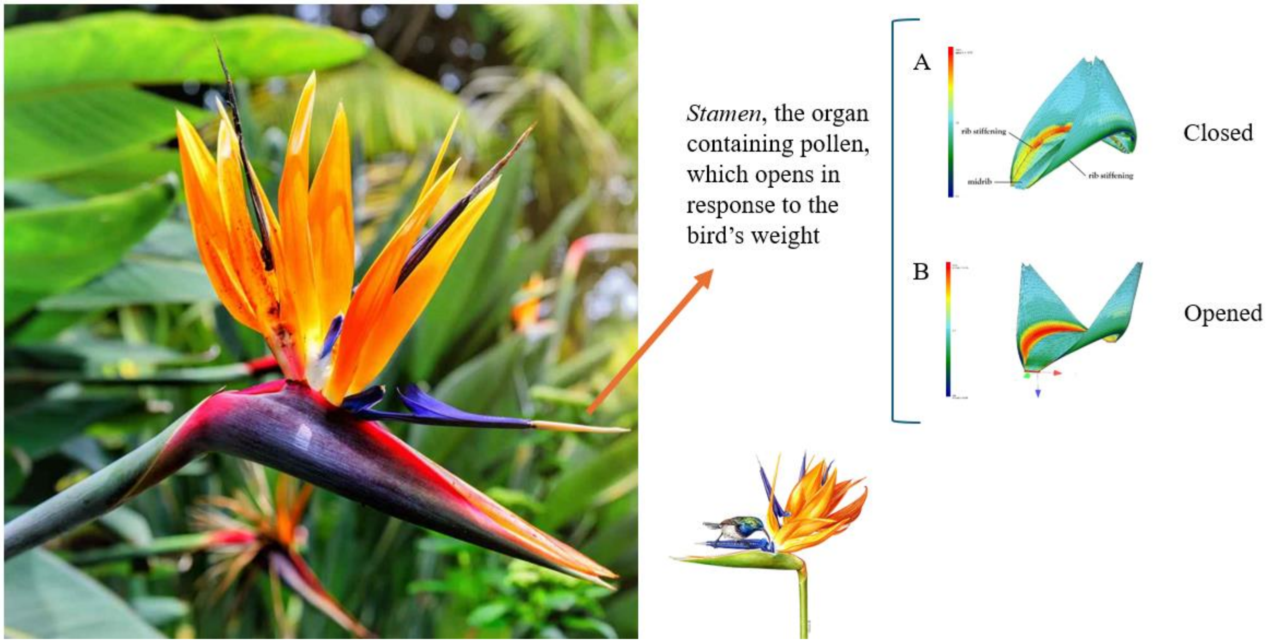


Figure 13 - The bird of paradise flower's purple-colored 'Stamen' opens up when a bird sits on it to search for nectar. As a result, the pollen inside the Stamen are exposed and they attach to the bird's feet, facilitating pollination. This shape change is known as lateral torsional buckling (LTB) which is classically regarded as a failure mode in architecture. However, the Flectofin™ mechanism utilizes this mechanism to enable light and temperature regulation in buildings. In OOB, this is employed using flaps made of fiber-reinforced polymers like GFRP. The A and B modes (right side of the figure) display the bending zones. This part of the figure was retrieved from (Salgueiredo & Hatchuel, 2016).

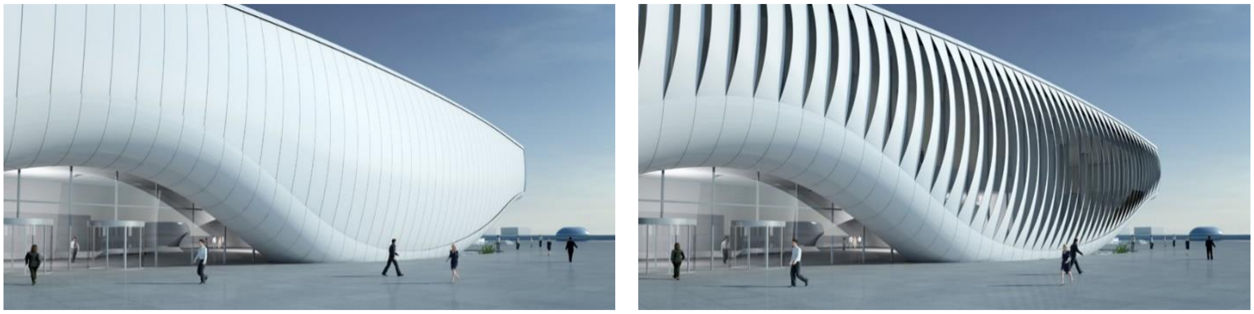


Figure 14 - OOB with closed lamallae (left) and open lamellae (right)

5. The TyssenKrupp Q1 building in Essen, Germany

Another example of an adaptive façade can be found in the TyssenKrupp Q1 building in Essen which opened in 2010. The Q1 building is a central part of the ThyssenKrupp Quartier in Essen, stands 54 meters tall and is designed with a transparent, frameless glass façade (figure 15). Its expansive atrium with large windows provides ample natural light, contributing to a spacious and open atmosphere (ArchDaily, 2013). To regulate temperature and lighting, the Q1 uses a unique "Mediterranean double skin" design, introduced by Renzo Piano, which combines a glass façade with an exterior envelope of sunshades to manage solar radiation. The envelope features a system of movable, stainless steel sunshades. The vertical fins, made of horizontal slats, twist to block direct sunlight or allow maximum daylight. The slats are made from corrosion-resistant stainless steel, with matte or glossy finishes depending on light angles, and they ensure offices stay bright even with sun protection active. The system is controlled by a sensitive mechanism that adjusts based on current weather conditions, providing optimal light and heat management throughout the day (Solla, 2024).

This design was a response to recent research questioning the energy efficiency of double-skin glass façades, especially with advancements in triple-glass units with argon-filled cavities and coatings reducing heat loss (U-values). Furthermore, research also suggests that in the summer, the solar heat gain, rather than U-values is the determining factor for the internal temperature of office buildings. However, closing the shades completely results in no natural light entering the building which is also suboptimal. To tackle this, the design solution was suggested for Q1 was a low U-value glass facade combined with adjustable sunscreens, limiting solar radiation when needed while still letting in some daylight. The exterior envelope was designed such that it contained several slats, moving in a similar way to fins, offering solar protection for the building. A weather station at Q1’s top sends signals to a central computer that controls the steering of each pair of slats based on their location on the building, and the angle and intensity of sunlight (figure 15; note the shape for the slats that is non-rectangular, thus creating an interesting texture as the slats rotate) (Solla, 2024).

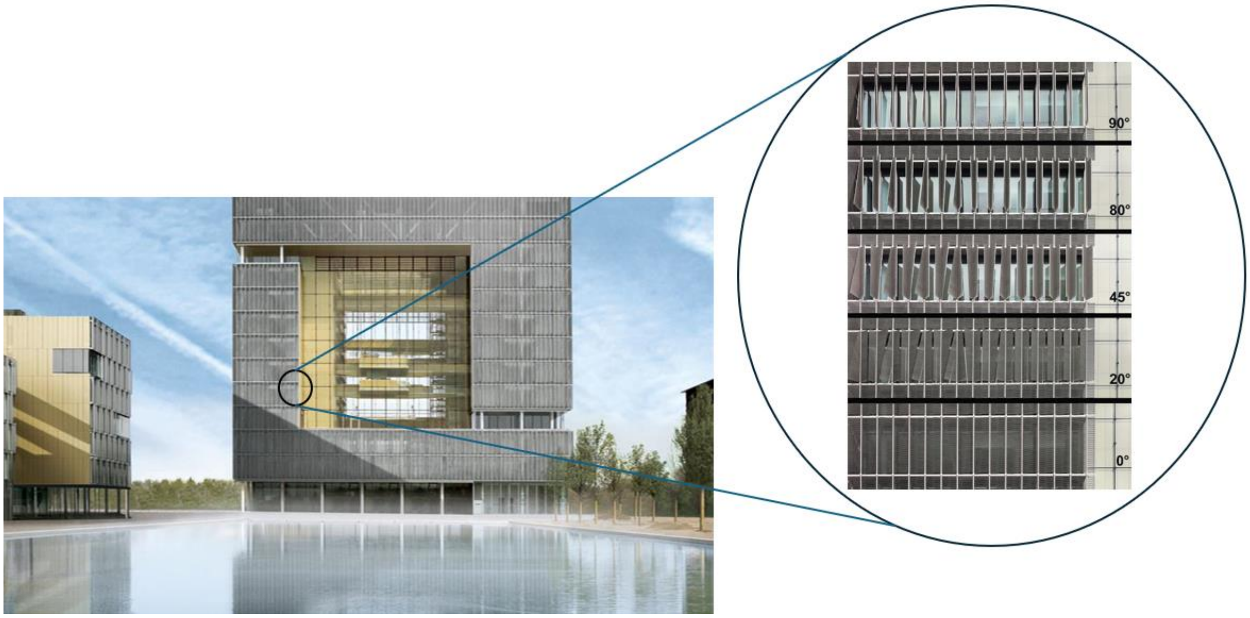


Figure 15 - ThyssenKrupp Q1 building has an exterior envelope over its glass façade which operates as an adaptive regulator for solar radiation. This exterior envelope is made up of several units which have a fin-like movement in order to allow daylight in, but still reduce solar radiation coming in to the building, in order to reduce its heating. The slats are connected to a weather station on the top of the building which calculates what the optimal rotation should be for each pair of slats based on the intensity and angle of sunlight, rotating each slat at different angles from 0° to 90°.

6. Esplanade Theatre in Singapore

The Esplanade Theatre is a two-story building located at Marina Bay near the historic Singapore River, which was completed in 2007. It was designed by DP Architects and Michael Wilford. Initially, the design faced criticism for being overly reliant on glass and reflecting Western aesthetics, which didn't suit Singapore's tropical climate. In response, the architects adopted a biomimetic approach, drawing inspiration from the tropical Durian fruit and sea urchin shells to create a unique skin for the building (figure 16). The spiky sunshades on the Esplanade's roof serve as protection from the sun, similar to the function of the Durian's spikes. On the sides, each shell features aluminum sunshields, with the longest shades on the east and west sides of the envelope where sun exposure is highest. Singapore is close to equator so the sunlight direction mainly remains the same. The resulting triangular windows provide shading and repetitive elements, which provide natural light, but prevent overheating and reduce HVAC usage, adapting to the local climate (figure 17). Additionally, this outer envelope made the theater a cultural landmark, since its design is based on local elements (Radwan & Osama, 2016; Verbrugghe et al., 2023).

- HVAC energy reduction (30 %)
- Capturing solar energy
- Reduction of artificial lighting (50 %)
- Cultural value of the structure

Figure 16 - The Esplanade's envelope inspired by the tropical Durian fruit. This envelope aims to limit the tropical solar radiation entering the building to prevent the building from overheating.

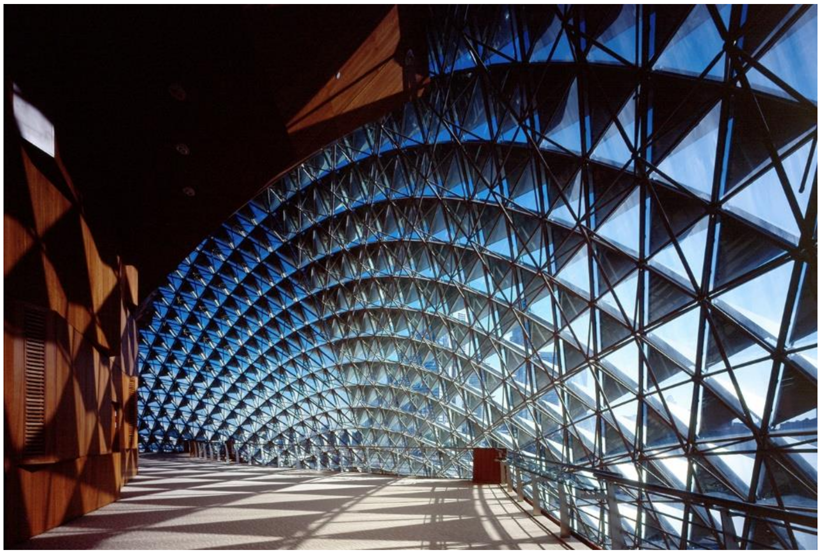


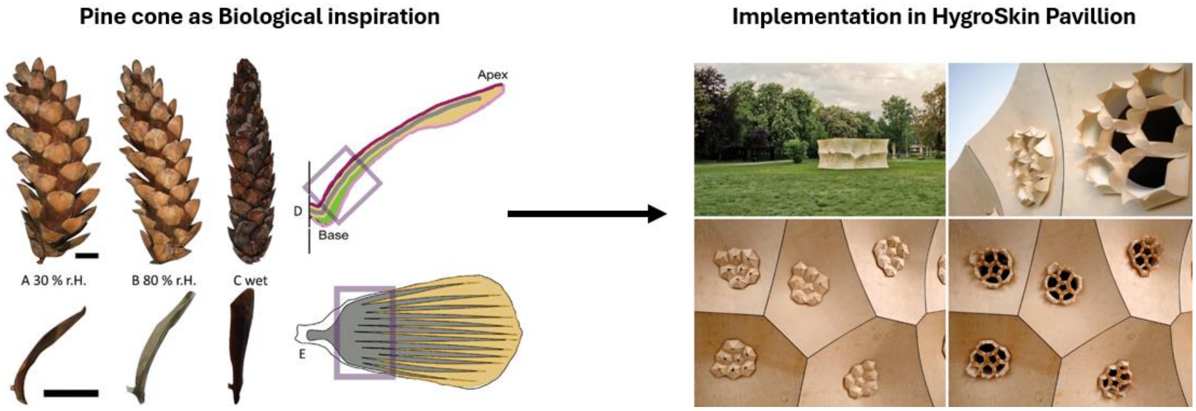
Figure 17 - the interior of the Esplanade theatre receives a controlled amount of natural light due to its outer envelope design, such that the use of HVAC systems are reduced. Since Singapore is located in an equatorial climate, the angle of sunlight remains relatively the consistent, and thus a static envelope was used instead of a dynamic one.

7. HygroSkin pavilion in Orleans, France

This pavilion has an adaptive façade which mimics spruce cones in responding to changes in environmental conditions (Uchiyama et al., 2020). It was developed to exhibit the properties and potential of wood in the future of architecture.

In the quest for more “intelligent” materials, wood's adaptability often goes unnoticed. However, Menges and Reichert from the Institute for Computational Design (ICD) at the University of Stuttgart have highlighted wood’s moisture-sensitive qualities, also known as “hygromorphic” qualities. Using the spruce cone’s changes in shape in response to moisture as an example, they maintain that wood has the potential to perform as a sensor, motor, and response mechanism. Wood’s hygromorphic properties are often cited as a downside in technology, but plants use this mechanism to enable motion. In spruce cones, the cellulosic tissue structure allows for shape changes essential for seed release, even after the cone has died. Essentially, the pinecone performs passive movements with only material, shape and humidity. When humidity increases the underside of each scale expands while the upper side remains the same size. Because of this difference, the scales curve upwards which closes the pinecone. Hygroscopic actuation in plants achieves movement without muscles, and in architecture, it offers a “no-tech” alternative for climate-responsive building envelopes, reducing reliance on high-tech systems and their energy requirements (Eger et al., 2022). Since Hygroscopic actuation in plants achieves movement without muscles, it offers a “no-tech” alternative for climate-responsive building envelopes, reducing reliance on high-tech systems and their energy requirements (Menges & Reichert, 2015).

The HygroSkin – Meteorosensitive Pavilion was developed as a modular, traveling structure (figure 18) and first exhibited in 2013 at the FRAC Centre in Orleans, France. It features 28 unique skin modules created by connecting elastically bent plywood panels with custom joints, forming conical surfaces that allow for humidity-responsive apertures. These 1,100 apertures open in low-humidity conditions (sunny days) and close in high humidity (rainy days), aligning with moderate climate changes (Menges & Reichert, 2015; Sommese et al., 2022).


Pine cone as Biological inspiration

Implementation in HygroSkin Pavillion

Figure 18 - The HygroSkin Pavilion in Orleans, France (right) features 28 unique skin modules created by connecting elastically bent plywood panels to joints. The resulting 1,100 apertures open in low-humidity (no rain) and close in high humidity (rain) conditions. Right image obtained from (ICD Stuttgart, 2013). This mechanism is inspired by the hygromorphic qualities of pine cones, which passively close in response to humidity to protect their seeds. Left image obtained from (Eger et al., 2022)

8. Pho’liage® shading device by ArtBuild architects

The Pho’liage® shading device, developed by ArtBuild, is a prototype kinetic system designed for autonomous solar shielding without the need for human or mechanical activation. Inspired by the opening and closing mechanisms of leaves and flower petals, it utilizes thermo-reactive and photosensitive materials to respond to variations in solar radiation. The design incorporates smart materials such as shape memory alloy (SMA) and Thermostatic Bimetals (TBMs) which require minimal energy and respond to temperature changes. When external temperatures exceed 25 °C, the petals open to create a protective curtain, preventing overheating in the building, and they close as temperatures drop, allowing natural light to enter (figure 21). Pho’liage® operates without the need for motorization or maintenance (during the warranty period), relying entirely on solar radiation for activation. While the photovoltaic (PV) cells contribute to heat loss due to the Joule heating effect during energy production, the interaction between the photo-sensitive (PV) and thermo-reactive (TBM) materials enhances the overall energy efficiency of the device by improving the reactivity of the actuator. Currently, the Pho’liage is at advanced prototyping stage, and focusing on adapting the shading system for various architectural contexts, experimenting with different petal shapes and configurations. According to ArtBuild, Pho’liage was to be implemented in 2022 as a pilot project at the new headquarters of the International Agency for Research on Cancer (IARC). However, the results of this pilot project are not yet published to the best of the author's knowledge (ArtBuild, 2019; Chayaamor-Heil, 2023; Sommese & Ausiello, 2023).

For context, French legislation from 2012 and 2020, has set limits for energy use of new buildings to a maximum average of 50 kWhEP/(m^2). Meanwhile, they have also set targets for providing thermal comfort for building residents particularly during heatwaves, particularly by promoting bioclimatic architecture, and adaptive façades which optimize energy efficiency and occupant comfort (Charpentier et al., 2022).

To address specific technical challenges—such as thermal and light regulation for building facades—designers looked at biological examples. Architect Steven Ware's background in biology played a crucial role in shaping the design process. The design inspiration came from nyctinastic plant movements (figure 19). These are the movements of plant leaves or petals, in response to the changes in light levels between day and night. The movement takes place within seconds to hours, and is regulated by changes in turgor pressure within the plant cells, specifically “pulvini” cells, located at the base of leaves or petals. Turgor pressure changes cause these structures to swell or contract, leading to the closing or opening of leaves or flowers. Nyctinastic movements allow plants to conserve water, protect themselves from temperature fluctuations, and optimize their exposure to light (Oikawa et al., 2018; Oliveira, 2023).

To mimic this mechanism, TBMs were chosen as they were workable, relatively affordable and because the ArtBuild's research lab had been experimenting with them since 2015. TBMs are alloys that expand and contract with temperature changes.. They utilize the shape memory of TBMs, where bands return to their factory-curved shape when heated by the sun, helping close gaps in the façade and protecting it from solar heat. The bending of TBMs depends on the difference in expansion rates between the material layers, temperature changes, and the thickness of the strips. Based on practical tests, the designers opted for **trilobal petal shapes**, as they offered both heat sensitivity, sound insulation and structural stability for outdoor use, despite exposure to wind and pollution. Additionally, in the tests, this design showed better performance in solar shading, especially with slower closing times during the cooling process. To provide corrosion protection for the thermostatic bimetals (TBMs) while optimizing the curving dynamics of the petals, the designers selected decorative coatings with a dark, matte finish (figure 20) to efficiently absorb solar heat, enhancing actuation responses (Charpentier et al., 2022). Furthermore, to reduce the quantity of TBMs required, ArtBuild is also investigating the use of biopolymers for the shading function, while relying on TBMs for the actuators. These biopolymers would be derived from renewable biomass sources, such as vegetable oils, corn starch, and recycled food waste (Charpentier et al., 2022).

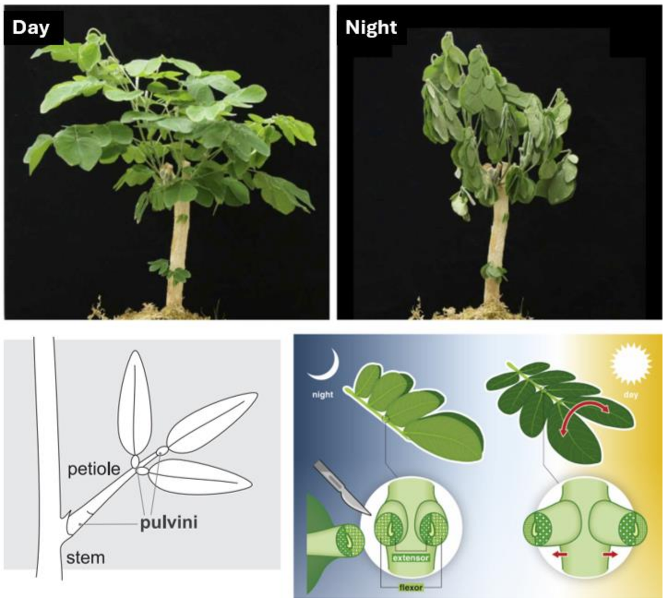


Figure 19 - Top: Pho'liage's design was inspired by nyctinastic plants, which open their leaves during the day and when there is sunshine to optimize light exposure. Nyctinastic movements are considered a part of the plant's circadian rhythm. Image from (Nakamura, 2024). Bottom: Schematic view of the mechanism regulating nyctinastic movements of plant leaves. Pulvini cells regulate the opening and closing of leaves as their turgor pressure changes in response to changes in the external temperature, light and humidity. The movement takes place within seconds to hours, depending on the species. Left image (Oliveira, 2023), right image (Oikawa et al., 2018).

Figure 20 - Reaction of coated and uncoated petals to sunlight, left side after 10 seconds and right side after 1 minute. The coating with a dark finish provides protection from corrosion, while minimizing the compromise in the curving dynamics, as the dark color maximizes sunlight absorption (Charpentier et al., 2022).

Figure 21 - Left: Simulated image of the IARC façade with Pho'liage adaptive shading, where a pilot was to be tested in 2022. Right: The tripolar prototype of Pho'liage made of TBM that respond to heat changes while maintaining rigidity, and are resilient when exposed to wind loads and pollution. They are now also investigating biopolymers to reduce the amount of TBMs required in the curving petals. Image credit: ArtBuild ®.

3.2. Air Regulation for Non-Thermal Purposes

1. Pearl River Tower (PRT) in Guangzhou, China

Completed in 2013, the PRT is a 310 meter tall, 71-level skyscraper which ranks 178th in the global height rankings for buildings. It primarily houses offices, and has won credible design awards such as the best tall building of the Asia/Australasia region in 2013 and the 10-year award of excellence in 2023 (Council on Tall Buildings and Urban Habitat, 2024).

The building was positioned to benefit from the sunlight and local wind patterns. It takes inspiration from sea sponges to consume less energy (figure 22). Each day, sea sponges pump and filter thousands of liters of water through their porous bodies, from which they obtain their food. Additionally, they provide shelter for various tiny organisms. Similarly, the tower features four large openings on its sculptural southern façade that capture the strong high-altitude winds (figure 23), and power the energy-generating vertical axis turbines. Using computational design and construction (CDC) modeling, the shape of the wind openings have been designed to accelerate the speed of winds going into them, to increase energy generation yield by the turbines. The turbines produce roughly 1million kilowatt hours of electricity per year (Bakalova, 2024; Gibson & Enns, 2020; Mirniazmandan & Rahimianzarif, 2017).

The PRT also harnesses solar energy through a photovoltaic system integrated with the building's external solar shading and glass façade. The tower's shape, angle, and south-facing orientation are designed to maximize exposure to the sun's path. Combined with other energy-saving HVAC approaches like radiant cooling, these features are reduce the building's energy consumption by 58–60% (Mirniazmandan & Rahimianzarif, 2017). It is estimated that the PRT's energy saving features (i.e. the biomimicry-based features described here, as well as its double layer façade which traps solar heat) generated roughly $13 million extra construction costs, which would take around 5 years to be returned through savings on energy bills and lower maintenance costs (Gibson & Enns, 2020).

Figure 22 - A group of Venus flower basket glass sponges (Euplectella aspergillum) providing shelter for a squat lobster (Imbler, 2021). Hexactinellids, or glass sponges, are exclusively marine and sponges largely restricted to the deep sea. They are distinguished by a complex skeletal anatomy, namely siliceous spicules with six rays intersecting at right angles. They have a large central cavity that allows water to pass through, enabling them to filter plankton and bacteria from the water for food. They cannot contract like other sponges but have a unique system for rapidly conducting electrical impulses, allowing them to quickly respond to external stimuli (Wörheide et al., 2012).

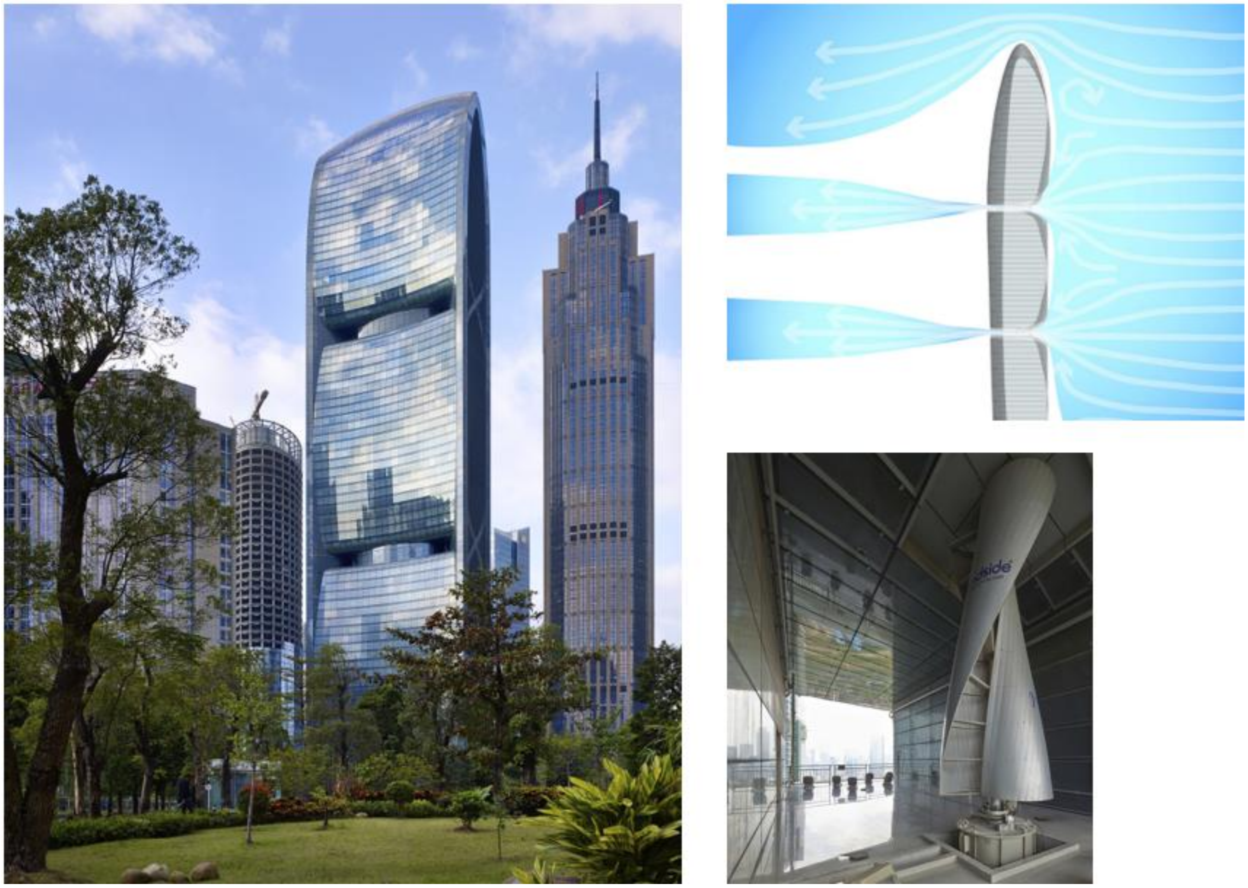


Figure 23 - Left: the design of the PRT in Guangzhou takes inspiration from sea sponges. Image obtained from (Council on Tall Buildings and Urban Habitat, 2024). Top right: the wind acceleration mechanism employed in the PRT (Gibson & Enns, 2020). The openings in the building suck in and accelerate winds to generate electricity using vertical axis wind turbines (bottom right – image from (Golenda, 2015)).

2. The Gherkin Tower in London, The UK

The 30 St Mary Axe, also known as the Gherkin, is a high rise commercial tower in London which was completed in 2003. It is 180 meters tall and has 40 floors. Having won multiple awards such as the Royal Institute of British Architects (RIBA) prize, it is an instantly recognizable structure in the city's crowded skyline. The name "gherkin" comes from the building shape's remarkable similarity to the smaller cucumber fruit used for pickling. The tower uses a diagrid exoskeleton structure which enables a column-free floor space, thereby resolving many unnecessary walls and roofs (Lama, 2021; Verbrugghe et al., 2023).

The Gherkin's designers were inspired by the Venus flower basket or *Euplectella aspergillum,* a western Pacific hexactinellid sponge (figure 22). This glass sponge is composed of glass-like structural particles made of silica. The tiny siliceous elements in its exoskeleton are known as *spicules*. These spicules connect in large numbers to form a remarkable pattern referred to as a "glass house." Essentially, this exoskeleton consists of a network of spicules that link together to create a matrix, defining the sponge's outer shape. The glass sponge thrives in an underwater environment with strong water currents. Its lattice-like exoskeleton and round-edges help distribute the forces from water currents and reduce the unavoidable stress (Ibrahim & Hosam Abd, 2018; Nkandu & Alibaba, 2018).

Similarly, the building's curved sides allow wind to flow smoothly around it, rather than deflecting down to street level and blasting pedestrians (figure 25). Since more air can flow around the side of a cylinder compared to the corner of a rectangle, wind speed increases, creating a higher negative air pressure at the building's rear. Gherkin's architects leveraged this effect to power a natural ventilation system. The building's main structure employs an aluminum-coated steel diagrid. The diagonal elements in a diagrid system are able to resist both gravity and horizontal loads due to their triangular arrangement. Compared to traditional tubular systems with non-diagonal frames, diagrid structures are significantly more effective at reducing shear deformation, while also requiring a smaller amount of materials: in Gherkin's case, 20 % less steel than a conventional moment-framed building. This makes these structures more material-efficient and lighter. This diagrid skeleton (figure 24 and 26) divides the tower into a series of vertical modules and make it column-free, allowing for open interior spaces, cut-away floor openings with revolving triangular atriums for natural lighting and ventilation (Küçük & Arslan, 2020; Nkandu & Alibaba, 2018).

The Gherkin's spiral shape is achieved through a 5-degree turning angle between each pair of floor plates, though all triangular windows used are flat. Six triangular sections have been removed from the circular floor plans to create light wells (figure 26), bringing in natural light and thus enabling office workers to make the most of the daylight that reaches the center of the circular floor plan (Küçük & Arslan, 2020).

Moreover, the tower's façade is a double-skin which maximizes sun exposure: the outer skin features mullions and triangular windows, while the inner wall consists of sliding glass doors regulated by a weather-responsive computer system. Between the two walls lies a space with horizontal shading devices to regulate sunlight trapping, as well as venting flaps which help hot air rise and exit the building. The double-skin façade effectively supports passive cooling, heating, ventilation, and lighting. To facilitate air dispersion within the structure, the light wells are interrupted every six floors, and equipped with operable mechanical windows along them (792 in total). External pressure differences created by twisting winds and the building's aerodynamic shape enhance this natural ventilation system and as a result, significantly reduce the need for air conditioning (Küçük & Arslan, 2020).

Nevertheless, the design has some drawbacks. The extensive use of glass in a large structure like the Gherkin Tower can present risks, as seen in 2005 when a glass panel fell from the 28th floor to the plaza below. Another issue with glass skyscrapers is sun glare, which can cause discomfort for pedestrians and drivers, sometimes leading to accidents due to impaired vision. Despite these challenges, the Gherkin Tower is more wind resistant, and more material efficient than many buildings of its size, thanks to the biomimetic design principles used by its designers (Nkandu & Alibaba, 2018; Verbrugghe et al., 2023).

Figure 24 - The Gherkin tower's diagrid exoskeleton and façade enhance its wind resistance and make it significantly more material effciient than conventional moment-frame structures of its size. This exoskeleton is inspired by the Glass sponge, which successfully handles the strong deep-ocean currents using its lattice-like network of glass-like particles. Left image retrieved from (Moussavi, n.d.), and right image from (Dursin, 2023).

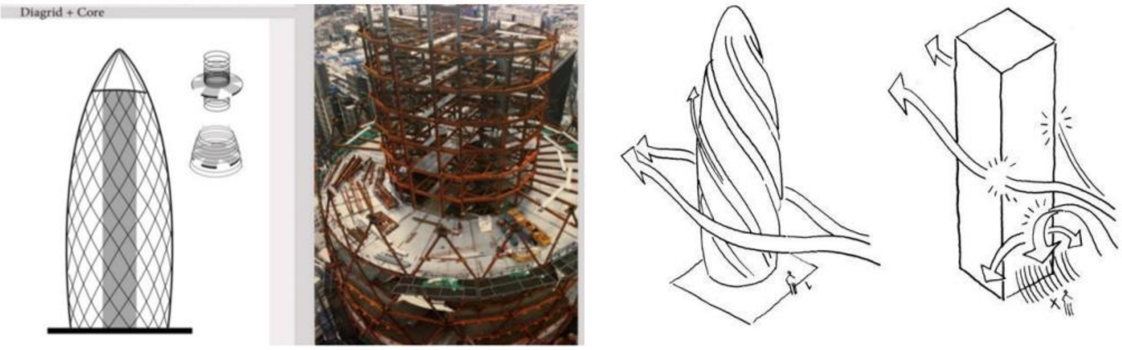


Figure 25 - The diagrid and core skeleton of the Gherkin. The tower's curvy shape allows a smooth flow of wind around it . . Left image obtained from (Nkandu & Alibaba, 2018), and right image from (Lama, 2021)

Figure 26 - Gherkin's light wells from exterior and interior angles. They bring in and disperse natural light to illuminate the circular floor plans. The darker line of glass consists of the blinds which are regulated based on the outdoor temperature and sunlight. For instance, if the outside temperature is between 20 and 26 ºC, they open to allow ventilation. The detail of the steel diagrid structure is also visible. Left image retrieved from (Moussavi, n.d.), and right image from (The Gherkin, 2024).

3.3. WATER REGULATION FOR BIODIVERSITY SUPPORT & INDOOR FARMING

1. The Sahara Forest Project (SFP) in Qatar, Tunisia, and Jordan

The Sahara desert used to be one of the main agricultural regions during the time of ancient Romans, providing more than two thirds of Rome's bread for over two centuries. This led to deforestation, loss of soil minerals and increased soil salination, and eventually desertification, creating one of the largest dry areas on earth (figure 27A). The Sahara Forest Project (SFP) is an international project which has an ambition to make the world's driest areas productive again, and eventually restore vegetation.

The SFP emulates an ecosystem in many ways. Nutrient-rich agriculture, no lasting pollutants, diversity, energy gains (from a local energy source), and regenerative as a unit. The SFP's greenhouses are cooled by evaporating seawater into the air to cool down and humidify the greenhouse to create optimal and sustainable growth conditions for crops such as cucumber, in arid regions (Atlas of the Future, 2021; Frederick, 2019). The evaporated water is also condensed into freshwater under the roof of the greenhouses and is then used for irrigation. The processes are powered by concentrated solar energy produced on the site. The greenhouses are all located within close distances to the sea. Seawater is pumped to the greenhouse, where fans blow desert air over sea water which creates a humid air stream within the greenhouse, and reduces indoor temperature. The condensation of moist air using cooling pipes results in freshwater which is used for irrigation. The brine (hypersalinated water) produced as a byproduct of freshwater production can be used to make salt as a commercial byproduct, thereby providing added value (figure 27 C and D). Additionally, energy is made in a concentrated solar power plant: solar energy is made into steam to turn turbines. In the Qatar plant, cucumbers were grown using half the freshwater needed in conventional methods (Akinaga et al., 2018; Atlas of the Future, 2021; Verbrugghe et al., 2023).

This freshwater production mechanism is inspired by the Namib Desert beetle's fog-harvesting ability (figure 27B). The Namib desert has an annual 1cm rainfall, but has fog events more often, coming from the Atlantic ocean during mornings. This beetle can capture fog with its back which contains hydrophobic and hydrophilic areas. The hydrophobic areas help capture and congregate water droplets, and the hydrophilic areas help transfer this water to the beetle’s mouth ((Frederick, 2019; Verbrugghe et al., 2023).

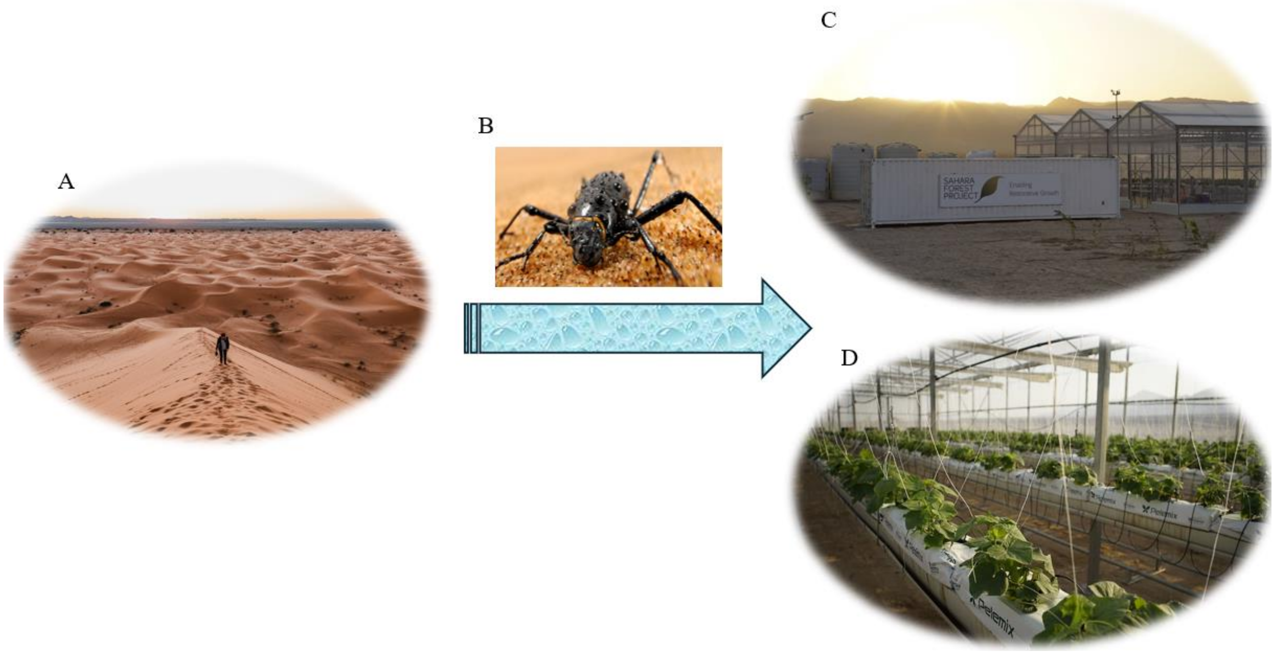


Figure 27 - A: Deforestation, loss of soil minerals have created large, dry, barren areas such as the Sahara. The SFP is a project which brings scientists, consultants and local governments together, with the aim to utilize salt water, available in abundance, to reverse this trend and restore vegetation in these arid areas. B: The SFP pioneers have studied the Namib desert beetle, who manages to capture enough water from the fog to survive in this climate. By tilting towards the humid wind, it congregates water droplets using the hydrophobic areas of its back. Then, the hydrophobic areas help it transfer these droplets to its mouth. (Image obtained from the Frederick, 2019). C & D: Using these evaporation and condensation principles and salt water pumped from the nearby sea, the SFP has built seawater-cooled greenhouses in multiple countries with a warm, arid climate including Qatar, Jordan and Tunisia to produce vegetables locally and sustainably using less water and only solar energy produced locally. If successful, the project is expected be scaled up (Images retrieved from Atlas of the Future, 2021; and Sahara Forest Project, 2022)

2. Marine Biomimetic Center (MBC) in Biarritz, France

France has seen a range of biomimetic projects being proposed and implemented in the past decade. The MBC in Biarritz is one of the four major public tenders in France that required a biomimetic, bioinspired, and/or regenerative building proposal in the past ten years. The center is a public building (2900 m^2) dedicated to research and innovation in biomimicry and marine biology, and the contract was awarded to the winning design by Patrick Arotcharen architecture in 2018, which is currently being realized (Cruz et al., 2022).

The project is also known as “Estran”, which in French means “foreshore”, and is currently being implemented by Bechu architects. The reason for this choice is that the building’s design aims to emulate a foreshore ecosystem (de Dampierre, 2019). A foreshore ecosystem, also known as the intertidal or tidal zone, is the area between high and low tide marks. This dynamic zone forms a crucial interface between land and sea, and is constantly influenced by tidal changes and wave action. The foreshore supports a range of coastal processes, such as sediment transport and nutrient cycling, which contribute to beach morphology and coastal ecosystem health. It’s also an important biodiversity hotspot, specifically for marine organisms adapted to fluctuating water levels, like crabs and mollusks. Moreover, it acts as a natural buffer, helping protect inland areas from erosion and storm surges (NOAA, 2019). By merging vernacular architecture and biomimicry, the Estran aims to create a self-sustaining ecosystem. Inspired by the foreshore’s tidal filtration, the roof acts as a “fifth facade” with Phyto-purification ponds that harvest rainwater and filter greywater (i.e. the relatively clean wastewater from bathroom sinks, kitchen appliances etc.). Additionally, a water storage reservoir is used to preserve the clean water (de Dampierre, 2019).

Next to blending in the natural landscape and housing the local biodiversity, Estran aims to adapt to environmental rhythms to optimize thermal comfort and energy efficiency. It does so by adapting to environmental and seasonal changes using “parametric strategies”; i.e. relying on algorithms and computational design tools to adjust design parameters based on specific environmental variables. By inputting data—such as sunlight angles, wind patterns, or material properties—architects can develop forms that respond dynamically to their surroundings. This approach allows for designs that maximize efficiency and enhance user comfort by tailoring the structure’s performance to its unique environment (de Dampierre, 2019). More detailed information on the design and the performance of Estran are not yet published as the project is currently being implemented.

Figure 28 - Depiction of the final product of project Estran for the "Marine Biomimetic Center of Excellence" in Biarritz. It is currently under implementation by Bechu architects and partners, The building emulates an foreshore ecosystem and incorporates the region's local species, while incorporating water filtration systems and rainwater storage. Image obtained from (de Dampierre, 2019).

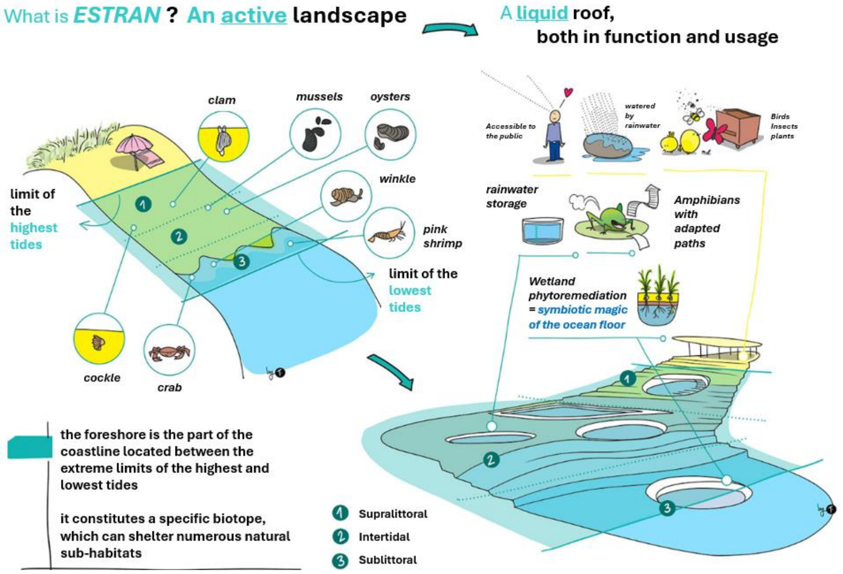


Figure 29 - An outline of how the Estran (foreshore) project incorporates local biodiversity by mimicking a foreshore ecosystem. The foreshore ecosystem forms an interface between land and sea, and consists of supralittoral (highest), intertidal (middle), and sublittoral (lowest) zones. It supports sediment transport and nutrient cycling, which form the basis for the growth of marine vegetation. This promotes phytoremediation, filtering out pollutants including metals, pesticides and oil (EPA, 2012). Furthermore, this allows colonization by local species such as clams in the supralittoral zone, mussels and oysters in the intertidal zone and crabs and pink shrimps in the sublittoral zone. As such, the foreshore is an important biodiversity hotspot. The Estran replicates these characteristics by incorporating a slopy liquid roof, a rainwater storage and a graywater treatment system. Figure information translated from French; Original image (de Dampierre, 2019) in Appendix A.

3. The Eden project (EP) in Cornwall, England

The EP is an attraction which is designed to entertain, educate and inspire visitors. Due to the successes of the EP project in Cornwall, it has gained international recognition and new EPs are currently being constructed (or already finished) in the UK, Dubai, China and Australia (The Eden Project, 2024). The first and main EP, located over a 130,000 sqm in Cornwall, was completed in 2001 and contains a park and greenhouses in the shape of domes. It is located in a clay pit (figure 31). The design challenge of the project was thus building structures on an uneven, unstable area of land. As such, the domes are supported by a series of geodesic structural frames (figures 30) which are lightweight, strong, and don't require internal support, allowing buildings on contoured clay to adapt to changes in soil conditions, such as developing and shrinking (Chairiyah & Sarwadi, 2018).

This shape of the domes is inspired by honeycombs and soap bubbles, and the domes are made of multiple hexagons, each filled with multiple layers of inflated ethylene tetrafluoroethylene (ETFE), a plastic polymer which is a lightweight material (weighing 1 % of double glazing) that acts as a great thermal insulator and costs a third of a conventional glass solution (Othmani et al., 2022; Verbrugghe et al., 2023). To increase temperature insulation without reducing light transmission, air is pumped into the layers between the ETFE pads. The amount of air is adjustable: during winter, more air is added for extra insulation, while in summer, the pads are partially deflated to improve cooling. These pads can also be easily detached from the steel framework, allowing for their replacement if a more efficient material becomes available (Gupta, 2021). This construction exemplifies efficient use of sunlight, adapting to changing (seasonal) conditions and employing modular components, all part of nature's design principles.

The EP includes two artificial enclosures, each replicating a natural biome (figure 30B). A biome is a naturally occurring community of plants and animals that occupy a major habitat. In Cornwall's EP, these artificial biomes showcase a humid tropical rainforest and a Mediterranean habitat. The tropical environment houses plants like banana trees, coffee, bamboo, and rubber from rainforests in Africa and South America, Australia and Asia. Its temperature and humidity are maintained at tropical levels. The Mediterranean biome, measuring 240 meters in length, houses plants from temperate rainforests in regions like Southern Africa, California, and the Mediterranean; namely olives and grape vines (Gupta, 2021).

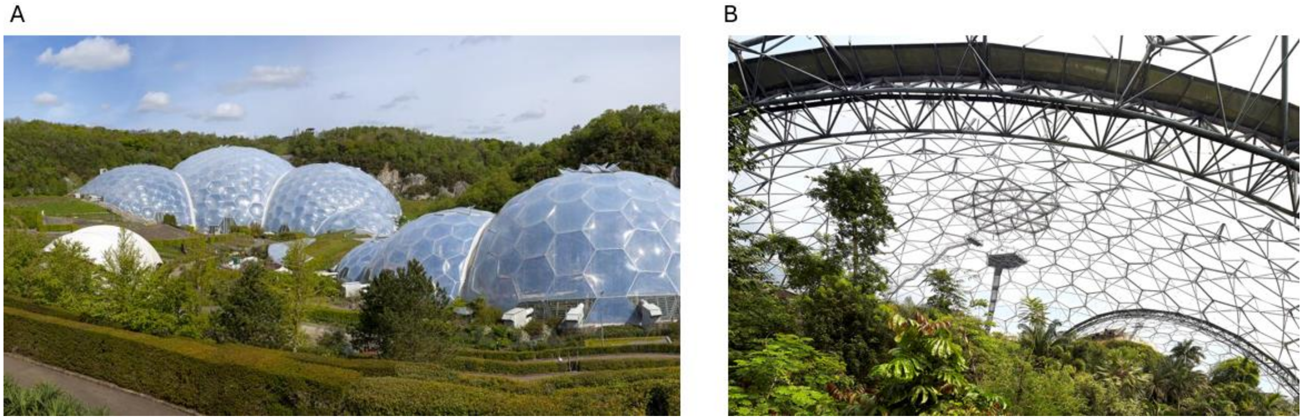


Figure 30 – A: Geodesic frames support the domes of the EP. B: The EP features two artificial enclosures that replicate natural biomes. One simulates a humid tropical rainforest with plants like banana trees, coffee, bamboo, and rubber; and the other represents a Mediterranean habitat, housing plants like olives and grape vines. Temperature and humidity levels are controlled to match each biome. Image A obtained from (The Eden Project, 2024) and B from (The Building Centre, 2021).

Figure 31 - The EP is located in a clay pit. The challenge of the project was to design buildings which could be sustained and adapted according to seasonal developments of the soil such as soil shrinkage. The designers overcame this challenge by opting for modular, lightweight domes made of replaceable ETFE pads, which are supported by geodesic structural frames which are also adaptable, lightweight, and modular. In practice, the ETFE is not a great acoustic insulator, and it can occasionally overheat the greenhouses during high temperatures as it lets in a lot of light. Additionally, while it is recyclable and its production comes with a lower impact than conventional glass and plastic, it is not biodegradable (Verbrugghe et al., 2023; Wang, 2022). Image from (The Building Centre, 2021).

4. DISCUSSION & FUTURE RESEARCH

In this overview, thirteen cases of biomimicry in the built environment were analyzed. Eight of these projects focused on thermal and visual comfort. They made buildings more energy efficient by reducing the need for air conditioning, thereby improving their sustainability performance. Five projects (CH2, OOB, Q1, HygroSkin and Pho'liage) focused on a form of adaptive façade to manage the incoming solar radiation. And adaptive façade can be a promising initial step to make buildings more responsive to their environment, but as a single measure, it hardly transcends the boundaries of contemporary architecture.

One project (SFP) used biomimicry to enable restorative farming in an arid area of land using seawater. This is an inspiring case of biomimicry supporting solutions to undo the (consequences of) damages inflicted on the planet, such as desertification. It does so while incorporating social and economic aspects, namely by providing fresh vegetables for the local population (societal), and building a business case around the salt produced as byproduct (economical).

The EP uses ecosystem-level biomimicry to provide a biodiversity hotspot for entertaining the public and engaging its attention. This approach can inspire similar projects on different scales in urban environments. Future research could explore the feasibility and benefits of establishing (exotic) biodiversity hotspots in urban areas, compared to typical greening projects.

At a more holistic level, the MBC aims to integrate with its local ecosystem by provisioning habitats on a "fifth façade", moving beyond merely improving its sustainability performance. By incorporating itself into the water cycles typical of that environment, it aims to develop a reciprocal relationship with its environment. In doing so, it also provides a valuable connection to nature for its inhabitants. This is an interesting example of how thinking beyond the conventional boundaries of human comfort can lead to designs that harmonize with the surrounding environment, rather than being a burden on it. Future research can explore this approach in other climates, such as that of the Netherlands. Furthermore, the integration of this approach as common practice in new public and residential buildings can be investigated, as well as pathways for improving its economic feasibility.

The PRT and the Gherkin both utilized biomimicry to reimagine the concept of "high-rise building". If the future of construction chooses to embrace high-rise buildings as a response to overpopulation in urban areas, such innovations are needed to make them less of a burden on resources. Local energy production (PRT), passive ventilation (Gherkin), and grey water treatment facilities are promising steps, but the complexity and high initial and life cycle costs of these structures highlight the need for more research, larger-scale prototypes, and real-life examples to set a foundation for future designers.

While conceptually simple, Biomimicry's practical application is more complex (Verbrugghe et al., 2023). The literature highlights significant barriers in acceptance of projects that include biomimicry. This is partly attributed to the lack of understanding among project owners, and partly to the scarcity of well-documented successful application cases. The former can be addressed by creating awareness among project owners via recurrent workshops to improve essential understanding, and project briefings involving more in-depth information regarding the biomimicry approaches used in the project and their functionality. The latter problem is likely to be alleviated as more (partially) replicable projects are implemented and there is more clarity over the quantifiable advantages and costs of a certain approach. Moreover, the application of biomimetic design in architecture and urban planning is fueled by advancements in biology and engineering. Key studies (such as (Fecheyr-Lippens & Bhiwapurkar, 2017)) highlight the urgency of cross-linking these fields is in order to enable innovation beyond simply mimicking natural forms. Establishing biomimetic design methods and developing educational programs are essential to raising awareness of the importance of integrating biology and engineering.

REFERENCES

Akinaga, T., Generalis, S. C., Paton, C., Igobo, O. N., & Davies, P. A. (2018). Brine utilisation for cooling and salt production in wind-driven seawater greenhouses: Design and modelling. *Desalination*, *426*, 135–154. https://doi.org/10.1016/j.desal.2017.10.025

AlAli, M., Mattar, Y., Mhd Amer Alzaim, & Salwa Beheiry. (2023). Applications of Biomimicry in Architecture, Construction and Civil Engineering. *Applications of Biomimicry in Architecture, Construction and Civil Engineering*, *8*(2), 202–202. https://doi.org/10.3390/biomimetics8020202

Ali, H. H., & Al Nsairat, S. F. (2009). Developing a green building assessment tool for developing countries – Case of Jordan. *Building and Environment*, *44*(5), 1053–1064. https://doi.org/10.1016/j.buildenv.2008.07.015

ArchDaily. (2013, February 4). *Q1, ThyssenKrupp Quarter Essen / JSWD Architekten + Chaix & Morel et Associés*. ArchDaily. https://www.archdaily.com/326747/q1-thyssenkrupp-quarter-essen-jswd-architekten-chaix-morel-et-associes

ArtBuild. (2019). *Pho'liage ® | Art Build*. Art Build. https://www.artbuild.com/lab/pholiage

Ask Nature. (2020, May). *Mound facilitates gas exchange :* AskNature. https://asknature.org/strategy/mound-facilitates-gas-exchange/

Atlas of the Future. (2021). *Greening the sands with the sea*. Atlas of the Future. https://atlasofthefuture.org/project/the-sahara-forest-project/

Badarnah, L. (2017). Form Follows Environment: Biomimetic Approaches to Building Envelope Design for Environmental Adaptation. *Buildings*, *7*(4), 40. https://doi.org/10.3390/buildings7020040

Bakalova, E. (2024, October 16). *Load-Bearer, Space-Maker: Considering the Contemporary Column*. Journal. https://architizer.com/blog/inspiration/stories/load-bearer-space-maker-the-contemporary-column/

Blanco, E., Cruz, E., Lequette, C., Raskin, K., & Clergeau, P. (2021). Biomimicry in French Urban Projects: Trends and Perspectives from the Practice. *Biomimetics*, *6*(2), 27. https://doi.org/10.3390/biomimetics6020027

Blanco, E., Pedersen Zari, M., Raskin, K., & Clergeau, P. (2021). Urban Ecosystem-Level Biomimicry and Regenerative Design: Linking Ecosystem Functioning and Urban Built Environments. *Sustainability*, *13*(1), 404. https://doi.org/10.3390/su13010404

Blanco, E., Raskin, K., & Clergeau, P. (2022). Reconnecting neighbourhoods with ecosystem functioning: Analysis of solutions from six international case studies. *Sustainable Cities and Society*, *77*, 103558. https://doi.org/10.1016/j.scs.2021.103558

Bragança, L., Mateus, R., & Koukkari, H. (2010). Building Sustainability Assessment. *Sustainability*, *2*(7), 2010–2023. https://doi.org/10.3390/su2072010

Caro, D., Lodato, C., Damgaard, A., Cristóbal, J., Foster, G. R., Flachenecker, F., & Tonini, D. (2023). Environmental and socio-economic effects of construction and demolition waste recycling in the European Union. *Science of the Total Environment*, 168295–168295. https://doi.org/10.1016/j.scitotenv.2023.168295

Ceebios. (2024). *Biomimétisme*. Ceebios. https://ceebios.com/biomimetisme/

Chairiyah, R., & Sarwadi, A. (2018). Application of Adaptive Structure based on Natural Inspiration on Biomimicry Architecture. *Journal of Architectural Design and Urbanism*, *1*(1), 40. https://doi.org/10.14710/jadu.v1i1.3247

Charpentier, L., Cruz, E., Nenov, T., Guidoux, K., & Ware, S. (2022). Pho'liage: Towards a Kinetic Biomimetic Thermoregulating Façade. *Environmental Footprints and Eco-Design of Products and Processes*, 367–401. https://doi.org/10.1007/978-981-19-1812-4_12

Chayaamor-Heil, N. (2023). From Bioinspiration to Biomimicry in Architecture: Opportunities and Challenges. *Encyclopedia*, *3*(1), 202–223. https://doi.org/10.3390/encyclopedia3010014

Circle Economy Foundation. (2024). *The Circularity Gap Report. The Built Environment in the Netherlands*. Www.circularity-Gap.world. https://www.circularity-gap.world/sectors

Council on Tall Buildings and Urban Habitat. (2024). *Pearl River Tower - The Skyscraper Center*. Www.skyscrapercenter.com. https://www.skyscrapercenter.com/building/pearl-river-tower/454

Cruz, E., Blanco, E., Aujard, F., & Raskin, K. (2022). Has Biomimicry in Architecture Arrived in France? Diversity of Challenges and Opportunities for a Paradigm Shift. *Biomimetics*, *7*(4), 212. https://doi.org/10.3390/biomimetics7040212

de Dampierre, L. (2019). *Projets | ESTRAN*. Bechuetassocies.com. https://www.bechuetassocies.com/en/projet/estran

Dijkstra, M. (2023, May). *Termite mounds reveal secret to creating "living and breathing" buildings that use less energy*. Www.frontiersin.org. https://www.frontiersin.org/news/2023/05/26/frontiers-materials-egress-complex-termite-mounds-ventilation/

Dursin, B. (2023, April 2). *Day 19/365 of Steel - The Gherkin*. SteelExplained.com. https://steelexplained.com/day-19-365-of-steel-the-gherkin/

Dutch Green Building Council. (2021). *Whole Life Carbon*. Https://Www.dgbc.nl/Themas/Circulariteit.

Eger, C. J., Horstmann, M., Poppinga, S., Sachse, R., Thierer, R., Nestle, N., Bruchmann, B., Speck, T., Bischoff, M., & Rühe, J. (2022). The Structural and Mechanical Basis for Passive-Hydraulic Pine Cone Actuation. *Advanced Science*, *9*(20), 2200458. https://doi.org/10.1002/advs.202200458

Encycle Technologies. (2018, July 25). *Home*. Encycle Inc., Swarm Logic – Powered by Data. Driven by Sustainability. https://www.encycle.com/

Energie in Nederland. (2021). *Energieverbruik Gebouwde omgeving in Nederland in 2021*. Energieinnederland.nl. https://www.energieinnederland.nl/cijfers/2021/energieverbruik/gebouwde-omgeving

Entrop, A. G., Halman, J. I. M., Dewulf, G. P. M. R., & Reinders, A. H. M. E. (2016). Assessing the Implementation Potential of PCMs: The Situation for Residential Buildings in the Netherlands. *Energy Procedia*, *96*, 17–32. https://doi.org/10.1016/j.egypro.2016.09.090

EPA. (2012). *A Citizen's Guide to Phytoremediation What Is Phytoremediation?* https://www.epa.gov/sites/default/files/2015-04/documents/a_citizens_guide_to_phytoremediation.pdf

European Environment Agency. (2023, October 24). *Greenhouse gas emissions from energy use in buildings in Europe*. Www.eea.europa.eu. https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-energy

European Environmental Agency. (2022). *Intro*. Europa.eu. https://climate-energy.eea.europa.eu/topics/energy-1/energy-and-buildings/intro

European Parliament. (2023). *How to preserve biodiversity: EU policy (video) | Topics | European Parliament*. Topics | European Parliament. https://www.europarl.europa.eu/topics/en/article/20200519STO79422/how-to-preserve-biodiversity-eu-policy-video

Eurostat. (2024a, February 27). *Renewable energy for heating & cooling up to 25% in 2022 - Eurostat*. Ec.europa.eu. https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20240227-2

Eurostat. (2024b, June 5). *Energy use in EU households in 2022 lowest since 2016*. @EU_Eurostat; Eurostat. https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20240605-2

Fecheyr-Lippens, D., & Bhiwapurkar, P. (2017). Applying biomimicry to design building envelopes that lower energy consumption in a hot-humid climate. *Architectural Science Review*, *60*(5), 360–370. https://doi.org/10.1080/00038628.2017.1359145

Frederick, E. (2019, November 27). *Could this desert beetle help humans harvest water from thin air?* Www.science.org. https://www.science.org/content/article/could-desert-beetle-help-humans-harvest-water-thin-air

Gibson, C., & Enns, E. (2020). *SUSTAINABLE DESIGN FOR TALL BUILDINGS Adapting cities through renewable energy sourcing*. https://umanitoba.ca/architecture/sites/architecture/files/2023-02/CP_cip2020_Gibson.pdf

Golenda, G. (2015, February 20). *Architecture Inspired by Nature: Biomimicry from Art Nouveau to Neo-Futurism - Architizer Journal*. Journal. https://architizer.com/blog/practice/details/biomimicry-binet-som/

Guarino, F., Athienitis, A., Cellura, M., & Bastien, D. (2017). PCM thermal storage design in buildings: Experimental studies and applications to solaria in cold climates. *Applied Energy*, *185*, 95–106. https://doi.org/10.1016/j.apenergy.2016.10.046

Gupta, M. (2021). CHALLENGES IN INTEGRATION OF BIOMIMICRY IN ARCHITECTURE: TOWARDS A REGENERATIVE APPROACH. *CHALLENGES in INTEGRATION of BIOMIMICRY in ARCHITECTURE:* https://www.academia.edu/45590545/CHALLENGES_IN_INTEGRATION_OF_BIOMIMICRY_IN_ARCHITECTURE_TOWARDS_A_REGENERATIVE_APPROACH

Hernández García, L. C., Monteiro, S. N., & Lopera, H. A. C. (2024). Recycling Clay Waste from Excavation, Demolition, and Construction: Trends and Challenges. *Sustainability*, *16*(14), 6265. https://doi.org/10.3390/su16146265

Hoogenboom, M. (2023, June 23). *Duurzaamheid in de Bouw: Trends en de Groene Bouwrevolutie — Prefound*. Prefound. https://www.prefound.nl/duurzaamheid-in-de-bouw-trends-en-de-groene-bouwrevolutie/

Ibrahim, N. M., & Hosam Abd. (2018). Biological modeling as a tool for promoting sustainable construction technologies and improving the energy efficiency. *International Conference for Sustainable Design of the Built Environment - SDBE London 2018*. https://www.researchgate.net/publication/343737564_Biological_modeling_as_a_tool_for_promoting_sustainable_construction_technologies_and_improving_the_energy_efficiency

ICD Stuttgart. (2013). *HygroSkin: Meteorosensitive Pavilion | Institute for Computational Design and Construction | University of Stuttgart*. Www.icd.uni-Stuttgart.de. https://www.icd.uni-stuttgart.de/projects/hygroskin-meteorosensitive-pavilion/

Imbler, S. (2021, September 9). A Swirling Vortex Is No Match for This Deep-Sea Sponge. *The New York Times*. https://www.nytimes.com/2021/09/09/science/sea-sponge-skeleton.html

ISO. (2023). *Biomimetics — Terminology, concepts and methodology*. Iso.org. https://www.iso.org/obp/ui/#iso:std:iso:18458:ed-1:v1:en

Jamei, E., & Vrcelj, Z. (2021). Biomimicry and the Built Environment, Learning from Nature's Solutions. *Applied Sciences*, *11*(16), 7514. https://doi.org/10.3390/app11167514

Jonkers, H. M. (2015). *Self-Healing Concrete Inspired by Bones — Innovation — AskNature*. Asknature.org. https://asknature.org/innovation/self-healing-concrete-cracking-repair-solution-inspired-by-bones/

Küçük, M., & Arslan, H. I. (2020). Investigation of Diagrid Structures Over Gherkin Tower. *Proceedings Article*. https://doi.org/10.38027/n12020iccaua316291

Lama, S. (2021, August). *A Report On Biomimicry in Architecture*. https://www.academia.edu/download/100696863/Report_on_Biomimicry_in_Architecture_Suman_Lama_.pdf

Learn Biomimicry. (2024, September). *What (really) is biomimicry?* Www.learnbiomimicry.com. https://www.learnbiomimicry.com/blog/what-is-biomimicry

Learnbiomimicry. (2022, December 6). *The Biomimicry Life's Principles Explained*. Www.learnbiomimicry.com. https://www.learnbiomimicry.com/blog/biomimicry-lifes-principles

Lienhard, J., Schleicher, S., Poppinga, S., Masselter, T., Milwich, M., Speck, T., & Knippers, J. (2011). Flectofin: a hingeless flapping mechanism inspired by nature. *Bioinspiration & Biomimetics*, *6*(4), 045001. https://doi.org/10.1088/1748-3182/6/4/045001

Living Future Institute. (2024). *About*. International Living Future Institute. https://living-future.org/about/

López-Hernández, D. (2023). Termite mound as nutrient hot-spots in savannah with emphasis in P cycling and the potential use of mounds as soil amendment. *Pedobiologia*, *99-100*, 150888. https://doi.org/10.1016/j.pedobi.2023.150888

Masselter, T., Poppinga, S., Lienhard, J., Schleicher, S., Knippers, J., & Speck, T. (2012). The flower of Strelitzia reginae as concept generator for the development of a technical deformation system for architectural purposes. *Uni-Freiburg.de*, 389–392. https://freidok.uni-freiburg.de/data/113827

Meischke, J. (2023, September 22). *The enormous potential of self-healing bio-concrete*. TU Delft. https://www.tudelft.nl/en/innovation-impact/pioneering-tech/articles/the-enormous-potential-of-self-healing-bio-concrete

Menges, A., & Reichert, S. (2015). Performative Wood: Physically Programming the Responsive Architecture of theHygroScopeand HygroSkin Projects. *Architectural Design*, *85*(5), 66–73. https://doi.org/10.1002/ad.1956

Mirniazmandan, S., & Rahimianzarif, E. (2017). Biomimicry, An Approach Toward Sustainability of High-Rise Buildings. *Iranian Journal of Science and Technology, Transactions A: Science*, *42*(4), 1837–1846. https://doi.org/10.1007/s40995-017-0397-4

Moussavi, F. (n.d.). *30 St. Mary Axe*. Harvard Design Magazine. https://www.harvarddesignmagazine.org/articles/30-st-mary-axe/

Nakamura, K. (2024, March). *Nyctinasty: the movement of plants*. Plantclub.io. https://www.plantclub.io/blog-en/nyctinasty-the-movement-of-plants

Never Enough Architecture. (n.d.). *The Eastgate Centre*. Never Enough Architecture. https://neverenougharchitecture.com/project/the-eastgate-centre/

Nkandu, M. I., & Alibaba, H. Z. (2018). Biomimicry as an Alternative Approach to Sustainability. *Architecture Research*, *8*(1), 1–11. http://article.sapub.org/10.5923.j.arch.20180801.01.html

NOAA. (2019). *What is the intertidal zone?* Noaa.gov. https://oceanservice.noaa.gov/facts/intertidal-zone.html

Oberst, S., Lai, J. C. S., & Evans, T. A. (2016). Termites utilise clay to build structural supports and so increase foraging resources. *Scientific Reports*, *6*(1). https://doi.org/10.1038/srep20990

Oikawa, T., Ishimaru, Y., Munemasa, S., Takeuchi, Y., Washiyama, K., Hamamoto, S., Yoshikawa, N., Mutara, Y., Uozumi, N., & Ueda, M. (2018). Ion Channels Regulate Nyctinastic Leaf Opening in Samanea saman. *Current Biology*, *28*(14), 2230-2238.e7. https://doi.org/10.1016/j.cub.2018.05.042

Oliveira, D. M. (2023). Slits in the wall! Pulvinar slits confer unique cell wall mechanics for leaf movement. *Plant Physiology*. https://doi.org/10.1093/plphys/kiad166

Oliveira, G. (2023, July 21). *Embracing Biomimicry in Sustainable Architecture: Nature's Blueprint*. UGREEN. https://ugreen.io/embracing-biomimicry-in-sustainable-architecture-natures-blueprint/

Othmani, N. I., Mohamed, S. A., Abdul Hamid, N. H., Ramlee, N., Yeo, L. B., & Mohd Yunos, M. Y. (2022). Reviewing biomimicry design case studies as a solution to sustainable design. *Environmental Science and Pollution Research*, *29*(46), 69327–69340. https://doi.org/10.1007/s11356-022-22342-z

Pearce, M. (2016a). *Council House 2 Building. Melbourne*. Www.mickpearce.com. https://www.mickpearce.com/CH2.html

Pearce, M. (2016b). *Eastgate Building Harare*. Mickpearce.com. https://www.mickpearce.com/Eastgate.html

Pedersen Zari, M. (2020). Biomimetic Urban and Architectural Design: Illustrating and Leveraging Relationships between Ecosystem Services. *Biomimetics*, *6*(1), 2. https://doi.org/10.3390/biomimetics6010002

Pedersen Zari, M., & Hecht, K. (2020). Biomimicry for Regenerative Built Environments: Mapping Design Strategies for Producing Ecosystem Services. *Biomimetics*, *5*(2), 18. https://doi.org/10.3390/biomimetics5020018

Phillips, A. C. (2015, September 21). *9 benefits of blending biomimicry and the built environment*. Trellis. https://trellis.net/article/9-benefits-blending-biomimicry-and-built-environment/

Radwan, Gehan. A. N., & Osama, N. (2016). Biomimicry, an Approach, for Energy Effecient Building Skin Design. *Procedia Environmental Sciences*, *34*, 178–189. https://doi.org/10.1016/j.proenv.2016.04.017

Reap, J., Baumeister, D., & Bras, B. (2005). Holism, Biomimicry and Sustainable Engineering. *Energy Conversion and Resources*. https://doi.org/10.1115/imece2005-81343

Rethinking The Future. (2019, August 22). *CHURCH NIANING | IN SITU architecture*. Rethinking the Future Awards. https://awards.re-thinkingthefuture.com/church-nianing-in-situ-architecture/

Sahara Forest Project. (2022). *Jordan*. Sahara Forest Project. https://www.saharaforestproject.com/jordan/

Salgueiredo, C. F., & Hatchuel, A. (2016). Beyond analogy: A model of bioinspiration for creative design. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, *30*(2), 159–170. https://doi.org/10.1017/s0890060416000044

Saxena, R., Rakshit, D., & Kaushik, S. C. (2020). Experimental assessment of Phase Change Material (PCM) embedded bricks for passive conditioning in buildings. *Renewable Energy*, *149*, 587–599. https://doi.org/10.1016/j.renene.2019.12.081

Shubbar, A. A., Sadique, M., Kot, P., & Atherton, W. (2019). Future of clay-based construction materials – A review. *Construction and Building Materials*, *210*, 172–187. https://doi.org/10.1016/j.conbuildmat.2019.03.206

Solla, I. F. (2024, October 7). *ThyssenKrupp Quarter facades: a giant's gentle skin*. Blogspot.com. https://facadesconfidential.blogspot.com/2010/12/thyssenkrupp-quarter-facades-giants.html

Sommese, F., & Ausiello, G. (2023). From Nature to Architecture for Low Tech Solutions: Biomimetic Principles for Climate-Adaptive Building Envelope. *The Urban Book Series*, 429–438. https://doi.org/10.1007/978-3-031-29515-7_39

Sommese, F., Badarnah, L., & Ausiello, G. (2022). A critical review of biomimetic building envelopes: towards a bio-adaptive model from nature to architecture. *Renewable and Sustainable Energy Reviews*, *169*, 112850. https://doi.org/10.1016/j.rser.2022.112850

Sorensen, C. (2024). *The Use of Biomimicry in Urban Planning and Design*. DigitalCommons@CalPoly. https://digitalcommons.calpoly.edu/crpsp/281/

Srishti. (2021, February 26). *"ONE OCEAN"- A Thematic Pavilion - Architect and Interiors India*. Architect and Interiors India. https://www.architectandinteriorsindia.com/projects/15066-one-ocean-a-thematic-pavilion

Teixeira, M. (2021). *EU sets more ambitious energy reduction targets …* ABN AMRO Bank. https://www.abnamro.com/research/en/our-research/raising-the-bar-eu-sets-more-ambitious-energy-reduction-targets-for-its

The Building Centre. (2021). *Eden Project*. Building Centre. https://90years.buildingcentre.co.uk/building/eden-project/

The Eden Project. (2024). *Architecture | Eden Project*. Www.edenproject.com. https://www.edenproject.com/mission/architecture

The Gherkin. (2024). *Building – The Gherkin*. Thegherkin.com. https://thegherkin.com/building/

TNO. (2023a). *Energy in the built environment | TNO*. Tno.nl/En. https://www.tno.nl/en/sustainable/energy-built-environment/

TNO. (2023b, August). *Verduurzaming gebouwde omgeving - Energy.nl*. Energy.nl. https://energy.nl/thema/technologie-en-energiesysteem/energievraag/gebouwde-omgeving/

Torres, J. (2024, June 19). *3D printed ceramic cooling tower takes inspiration from termite mounds*. Yanko Design - Modern Industrial Design News; Yanko Design. https://www.yankodesign.com/2024/06/19/3d-printed-ceramic-cooling-tower-takes-inspiration-from-termite-mounds/

TU Delft. (n.d.). *Self healing concrete-materials that can repair itself*. TU Delft. Retrieved October 4, 2024, from https://www.tudelft.nl/innovatie-impact/samenwerken-met-tu-delft/octrooien/selectie-van-tu-delft-patent-portfolio/self-healing-concrete-materials-that-can-repair-itself

Uchiyama, Y., Blanco, E., & Kohsaka, R. (2020). Application of Biomimetics to Architectural and Urban Design: A Review across Scales. *Sustainability*, *12*(23), 9813. https://doi.org/10.3390/su12239813

UN Environment. (2024, March 6). *Global Status Report for Buildings and Construction*. UNEP - UN Environment Programme. https://www.unep.org/resources/report/global-status-report-buildings-and-construction

VentureWell. (n.d.). *Biomimicry Principles*. VentureWell. https://venturewell.org/tools_for_design/biomimicry/biomimicry-principles/

Verbrugghe, N., Rubinacci, E., & Khan, A. Z. (2023). Biomimicry in Architecture: A Review of Definitions, Case Studies, and Design Methods. *Biomimetics*, *8*(1), 107. https://doi.org/10.3390/biomimetics8010107

Wang, T. (2022, March 30). *Structural Membranes: Exploring ETFE and PTFE Synthetic Polymers in Architecture - Architizer Journal*. Journal. https://architizer.com/blog/practice/materials/etfe-ptfe-synthetic-polymer-architecture/

Weisser, W. W., Hensel, M., Barath, S., Culshaw, V., Grobman, Y. J., Hauck, T. E., Joschinski, J., Ludwig, F., Mimet, A., Perini, K., Roccotiello, E., Schloter, M., Shwartz, A., Hensel, D. S., & Vogler, V. (2022). Creating ecologically sound buildings by integrating ecology, architecture and computational design. *People and Nature*, *5*(1), 4–20. https://doi.org/10.1002/pan3.10411

Wörheide, G., Dohrmann, M., Erpenbeck, D., Larroux, C., Maldonado, M., Voigt, O., Borchiellini, C., & Lavrov, D. V. (2012). Deep Phylogeny and Evolution of Sponges (Phylum Porifera). *Advances in Sponge Science: Phylogeny, Systematics, Ecology*, *61*, 1–78. https://doi.org/10.1016/b978-0-12-387787-1.00007-6

World Business Council for Sustainable Development. (2023, August 4). *Transforming the Built Environment – WBCSD*. WBCSD. https://www.wbcsd.org/actions/transforming-the-built-environment/

Yu, Y., Yazan, D. M., Bhochhibhoya, S., & Volker, L. (2021). Towards Circular Economy Through Industrial Symbiosis in the Dutch Construction Industry: A Case of Recycled Concrete Aggregates. *Journal of Cleaner Production*, 126083. https://doi.org/10.1016/j.jclepro.2021.126083

Zhu, Q., Zhang, X., & Luo, J. (2023). Biologically Inspired Design Concept Generation Using Generative Pre-Trained Transformers. *Journal of Mechanical Design*, *145*(4). https://doi.org/10.1115/1.4056598

Zulkefli, N. S., Mohd Rahim, F. A., & Zainon, N. (2022). Bridging BIM and LCSA to Greening Existing Buildings: From A Literature Review to Development of Conceptual Framework. *IOP Conference Series: Earth and Environmental Science*, *1074*(1), 012022. https://doi.org/10.1088/1755-1315/1074/1/012022

APPENDICES

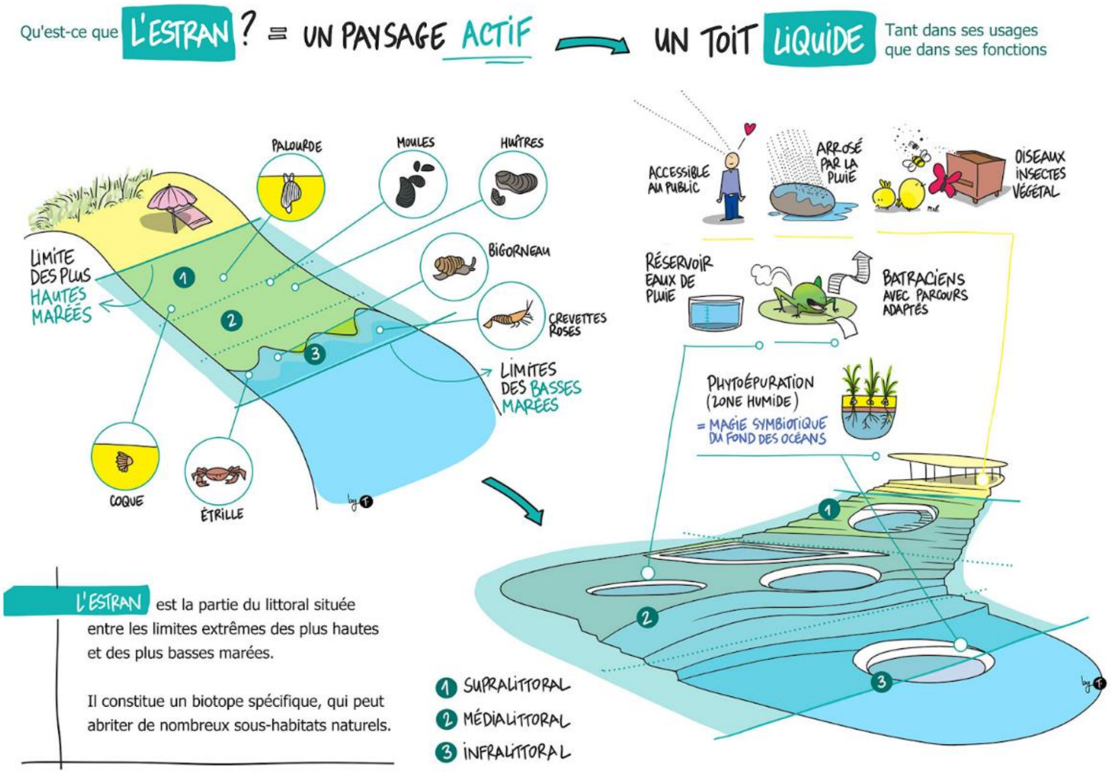
APPENDIX A. TABLES & FIGURES

Table A1: Nature's design principles. Information obtained from (Learnbiomimicry, 2022) and (VentureWell, n.d.).

Design principle	Description
Evolve to survive	Evolve strategies that work in the local environment Reshuffle information
Be resource efficient (material and energy)	Rely on sunlight and wind power Use low energy processes and only the amount of energy that is needed Curb excesses from within Multi-functional designs Recycle all materials Design forms that fit the function
Adapt to changing conditions	Incorporate diversity, resilience and self-renewal
Be locally attuned and responsive	Use locally and readily available materials and energy resources Leverage and reward cooperative relationships Use cyclic processes and feedback loops
Use life-friendly chemistry	Use chemistry *in* water and *with* water Use chemistry and materials that are safe for living beings
Integrate development with "growth"	Employing modular and nested components Organizing fractally: - Fractals are patterns that repeat at different scales, allowing growth without changing form. Like a snail's shell that expands by adding the same shape, or a tree's complex structure from a simple branching pattern, fractal systems grow naturally without

	needing new plans for different scales. Maintain self-similarity, while not looking identical at every level Building from bottom up: - For components: employing additive methods like 3D printing or small pre-fab parts to reduce waste and increase flexibility. - For systems, using design networks where nodes create the structure through their connections. This nature-inspired approach is more robust, flexible, and scalable than top-down designs.

Figure A1: Estran project's liquid roof which hosts the local species. Original figure, retrieved from (de Dampierre, 2019).



L'ESTRAN est la partie du littoral située entre les limites extrêmes des plus hautes et des plus basses marées.

Il constitue un biotope spécifique, qui peut abriter de nombreux sous-habitats naturels.

Illustration - version esquisse - **by Tatienne** - www.tatienne.fr

APPENDIX B: SOME PROMISING COMPANIES & STARTUPS

1. *Encycle's Intelligent HVAC optimization system*

Encycle's intelligent HVAC optimization systems utilize machine learning to optimize electricity consumption in a building and reduce peak electricity use by the its HVAC systems without needing a centralized server. Individual controllers coordinate with each other like swarming bees, creating an emergent property, meaning that the performance of the system as a whole is greater than the sum of all individual units (Encycle Technologies, 2018). Emergent properties are typically seen in nature's complex systems such as living organisms, where the whole is greater than the sum of individual components. For instance, a single bee is simple, but when many bees form a swarm, they behave as a sophisticated super-organism. While emergent behaviors are hard to predict, they can be simulated in virtual environments. Ultimately, designing for emergence creates robust systems with minimal resources and infrastructure (VentureWell, n.d.)

2. *Basilisk's Self-healing Concrete*

Concrete is one of the most widely used materials globally, with around eight billion cubic meters produced annually. Much of it must withstand exposure to water, leading to issues like cracking. Repairs are challenging and dangerous cracks in structures like bridges need urgent attention. "Concrete rot" is a misleading but commonly used term to describe a major issue in concrete construction. When water seeps into a concrete structure, it reaches the steel reinforcement, causing rust. As the steel rusts and expands, it leads to further cracks in the concrete. TU Delft spin-off Basilisk is addressing this problem with its self-healing concrete, resulting in fewer repairs and a notable reduction in CO2 emissions.

Self-healing concrete or bio-concrete gets inspiration from the mechanism with which bones self-repair. incorporates bacteria spores that release limestone as a filling agent for cracks in concrete. The self-healing agent consists of two key components: bacterial spores and calcium lactate nutrients. These are stored separately in expanded clay pellets or compressed powder granules, which are a few millimeters in size and mixed into the wet concrete. Concrete has a highly alkaline pH of around 13, so the bacteria must come from a robust strain. They also need to endure the mixing process and remain dormant for years before finally activating to perform their repair work when cracks appear. Bacillus species *Sporosarcina pasteurii* and *Bacillus pseudofirmus* are ideal for self-healing concrete because their spores can survive in a dormant state for decades without food or oxygen. In concrete, they remain inactive until cracks appear, which would then allow water and oxygen to enter. Once reactivated, they feed on lactate, combining calcium with carbonate ions to produce calcite (limestone), which seals the cracks. After the crack is sealed, moisture is blocked from entering, preventing further weakening; making this a desirable solution for damp environments like underground spaces.

Self-healing concrete has significant potential in reducing repair costs for existing structures. For new constructions, it offers better water protection and requires 30 % – 40 % less steel reinforcement, saving money while cutting CO2 emissions. To bring this innovation to market, TU Delft enlisted Bart van der Woerd, a concrete maintenance specialist with decades of experience on major infrastructure projects in the Netherlands. Nevertheless, concrete companies are generally conservative in adopting innovations, as if something goes wrong, the reputation of commissioning authorities and also clients would be impacted. One option to circumvent this can be the creation of a risk fund, as an alternative to subsidies, which would provide support if something does not go as planned in a major project. Experimentation and its inherent risks are a critical requirement of innovation (Jonkers, 2015; Meischke, 2023).

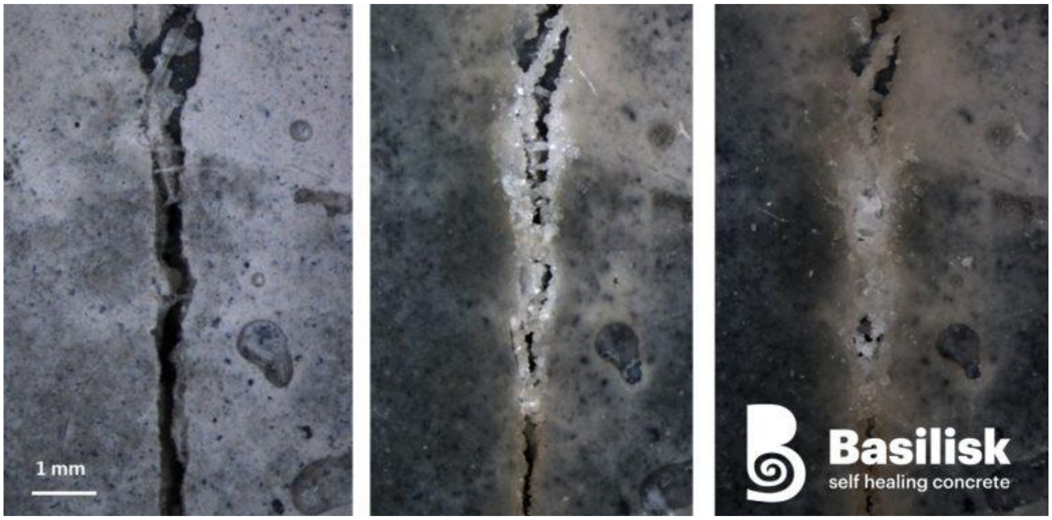


Figure B1 - Cracks healing within the concrete structure, closing off moisture's entry path.

Table B1 - A list of relevant companies & their fields. They are sorted based on location, in alphabetical order.

# Number	Company name	Location	Value proposition	LinkedIn
1	**Fairm**	Netherlands	Bio-based materials for construction, made by fermentation	Fairm
2	**Finch Buildings**	Netherlands	Design and development of sustainable buildings made from solid timber. Prefabricated modular units.	Finch Buildings
3	**Seenons**	Netherlands	IT solution to connect business waste to a second life (e.g., paper, PMD, coffee grounds)	Seenons
4	**Sustainer**	Netherlands	Software for (flexibly) designing modular houses	Sustainer
5	**The New Makers**	Netherlands	Circular homes for municipalities, housing corporations and investors	TheNewMakers
6	**The New Materialist**	Netherlands	Circular, aesthetic materials with robust performance	The New Materialist
7	**Visibuilt**	Denmark	Bio-based road construction	Visibuilt
8	**Ottan**	England	high-end biomaterials for designers that are upcycled from green waste such as nut shells, fruit peels and grass; to replace natural wood and ceramics (for acoustics, water resistance)	OTTAN
9	**CCB Greentech**	France	Wood-based concrete	CCB Greentech
10	**EASI ZERo**	France	Easy-to-install global building envelope system for efficient energy renovation with a near zero energy balance and CO2 emission. Project has received EU Horizon funding.	EASI ZERo
11	**Tocco**	France	Regenerative materials	tocco
12	**Woodoo**	France	Wood composite material for construction, made from underused hardwood	Woodoo

13	**Mimbiosis**	Germany	Mycelium panels (for acoustics, thermal insulation) made from textile waste	MIMBIOSIS
14	**Polycare**	Germany	Generation 4 Masonry system using geopolymer-based concrete (70 % less emission than trad. concrete)	Polycare
15	**YcoLabs**	Germany	Mycelium-based insulation solutions	YcoLabs - circular building insulation
16	**Mogu**	Italy	Mycelium technologies for interior and architecture	MOGU
17	**Leko Labs**	Luxembourg	AI-optimized and robotic manufacturing of construction materials	LEKO Labs
18	**Agoprene**	Norway	Bio-based foam as a replacement for oil-based foams	Agoprene
19	**Glulam Solutions Ltd.**	Scotland	Timber engineering contractor; supplying cross-laminated timber and floor, wall, roof panels for domestic and commercial clients.	Glulam Solutions Ltd
20	**GAIA Biomaterials AB**	Sweden	“Biodolomer” as an alternative for plastics	GAIA BioMaterials AB
21	**Modvion**	Sweden	Produces wind turbines from laminated wood	Modvion
22	**Woodcomposite Sweden**	Sweden	Wood compounds to replace plastics	Woodcomposite Sweden
23	**Kuori**	Switzerland	B2B plastic replacements for fashion, outdoor equipment and tools, with a carbon footprint 60 % lower than conventional plastics.	KUORI
24	**Swiss Wood Solutions AG**	Switzerland	Technology and business incubator for resource-conserving innovations based on wood from local, eco-managed sources to replace tropical wood and plastic.	Swiss Wood Solutions AG