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BIOMIMICRY APPROACH TO ACHIEVING THERMAL COMFORT IN A HOT CLIMATE

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Abstract

Biomimicry, a rapidly emerging branch of science, is being widely applied in various disciplines. A biomimicry design approach considers natural forms, structures and process as the main source of inspiration for problem solving. It is often argued that natural solutions to problems are sustainable and proven to work for billions of years, unlike human solutions that may be reliant on unsustainable resources and are subject to failure. Biomimicry therefore has great potential as an innovative design methodology in architecture and sustainable design.

Through literature review and digital simulation, this paper explores the potential of enhancing thermal comfort levels of the study building by applying a number of strategies inspired by a natural organism.

The study was conducted on a G+2 office building located in the UAE, in the west of the capital city of Abu Dhabi where the climatic conditions are above comfort levels most of the year. The desert snail was selected to extract survival strategies in the extreme desert heat.

Results show a drop in energy consumption that ranges between 3% and 19%, when strategies based on lessons learnt from the desert snail are applied.

Keywords: Biomimicry, Sustainable Design, Ecotect Software, Thermal Comfort.

INTRODUCTION

Biomimicry is the science of emulating natural methods to solve problems. Biomimicry involves imitating forms and structures of natural elements as well as mechanisms and technologies. The popularity and widespread adoption of this science today is largely attributed to Janine Benyus, a scientist and the author of *Biomimicry Innovations Inspired by Nature*, a highly influential book that was published in 1997. [2]

According to Benyus, the emergence of this new branch of science is related to an increasing awareness among humans that they are a part of a larger entity and a bigger system that managed to survive for 3.8 million years and that they should learn from this system and extract solutions to the different problems they face. [15]

Biomimicry as an approach to problem solving has significant potential since other organisms in nature face, or have faced, many of the same problems that humans encounter. Unlike human solutions that depend primarily on non-renewable resources and are subject to failure, natural solutions are tested and proven to work under real life conditions.

Biomimicry applications cover a wide range of disciplines such as medicine, agriculture, aerodynamics, architecture, industrial design and human safety. It is argued that many modern-day technologies and inventions already existed in nature before being developed by humans. Examples include airplanes that imitate the flying mechanisms of birds and ultra-sound scanning that imitates the night vision of bats using sound waves.

In this study, Biomimicry is used as a methodology to create a climate responsive architecture, with the objectives of producing increased thermal comfort levels for occupants, and reducing energy consumption.

1. LITERATURE REVIEW

Various studies have been carried out to explore the potential of applying Biomimicry to enhance the thermal performance of buildings, and to identify possible approaches. A study conducted in 2013 explores the potential of imitating the characteristics of human skin in the design of a building façade in order to improve the thermal performance of the building. A three-layered façade system was proposed. Each layer is designed to mimic certain characteristics of the skin. The first layer, a synthetic, exterior fur, imitates hair. The second layer is an internal fluid perfusion, and the last layer is an interior perspiration-evaporation surface. Results of the study show that ~35 W/m2 of cooling was provided by the façade by imitating human skin thermoregulation characteristics. [10]

In 2012, Frakgou and Stevenson investigated the effectiveness of mimicking the thermal performance of beehives for application in capsule hotels in in Tokyo. This study argues that the thermal requirements of bee colonies are similar to those of humans, and that the structure of the beehive is similar to that of the capsule hotel. Thus, mimicking beehives has the potential to enhance thermal comfort and reduce cooling loads. Digital simulations showed that mimicking the thermal performance of beehives did in fact increase thermal comfort levels for capsule hotel occupants, while reducing cooling loads. [5]

Another study conducted in 2012 looks into the possibility of designing a façade cladding component by mimicking the feathers of the Gentoo Penguins of Antarctica. Crucial to the penguins' survival in extreme cold weather, these feathers are proven to be a highly efficient insulating material. The researchers analyzed the layers of the penguins feathers and imitated their characteristics in the cladding layers of the façade. Digital simulation was conducted to compare a conventional façade to the bio-inspired façade on an office building in Sheffield. The study revealed that the façade cladding layers inspired by the structure of penguin feathers enhanced the thermal performance of the building. [1]

A number of studies have also focused on defining possible biomimicry approaches in Design. A study conducted in 2012 argues that a biomimicry approach to design must go beyond the formal characteristics of living organisms, to study processes and systems. This paper also argues that a biomimicry approach to architecture and interior design has significant potential to increase thermal comfort in spaces, and to enhance daylight levels. It is anticipated that this field will continue to grow, and will set new sustainable design standards. Two approaches to biomimicry design are identified in this study: (1) A problem-based, or top-down approach, which defines a problem and looks for solutions in nature; and (2) A solution-based or bottom-up approach, where knowledge in biology leads to the development of innovative designs. [12]

A study conducted in 2007 argues that biomimicry has great potential for the design of more sustainable buildings. It further argues that it is important to identify biomimicry design approaches, to enable designers to integrate them into their design process. In this paper, a framework for biometry applications in design was developed. The proposed framework is divided into levels of mimicry: the first level entails imitating an organism; the second, imitating a behavior; and the third, imitating an ecosystem. Each level is further classified into five dimensions of mimicry: form, material, function, process, and function. [11]

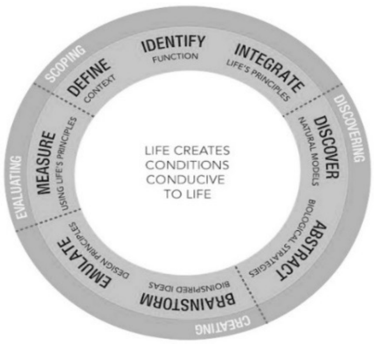
2. STRUCTURE AND METHODOLOGY

According to the Biomimicry 3.8 institute [3], the biomimicry thinking diagram (Figure 1) describes ways of integrating Biomimicry into the design process. The diagram suggests four stages. The first is 'scoping', which involves the identification of the problem for which solutions from nature are to be explored. The next step is to 'discover' the survival mechanism of a species that encounters a similar problem to the one identified. After this, strategies inspired by nature are proposed. Finally, an evaluation process takes place in order to assess the successes and failures of these strategies. The biomimicry thinking process adopted in this study consists in three parts: Scoping, Discovering, and Creating & Evaluating. Scoping includes analysis of both the study building and it's climate, in order to identify areas of potential improvement in terms of climate responsiveness and energy efficiency. In Discovering phase, natural concepts and life mechanisms are explored and analyzed. In this section number of nature-inspired strategies to enhance thermal comfort levels for the occupants and to increase energy efficiency are proposed.

Proposed strategies are then evaluated using digital simulation and a literature review.

Figure 1. Biomimicry thinking [3]

3. SCOPING



3.1. General Description

The building proposed for the study is the Centre of Excellence for Applied Research & Training (CERT) headquarters, a 30m X 20m (G+2) office building located in the UAE (Figure 2). The building is situated in the west of Abu Dhabi, on an East-West running street, within the Higher Colleges of Technology (HCT) complex.

The building is a simple box with a slanted roof. It is oriented along the southeast - northwest axis. Two of the main façades are fully glazed (northwest & southwest). The building envelope is mainly composed of two materials: glazing and aluminum cladding. A few other low-rise buildings surround the study building (Figure 3), and vegetation is limited to a simple grid of grassed areas and a number of decorative trees.

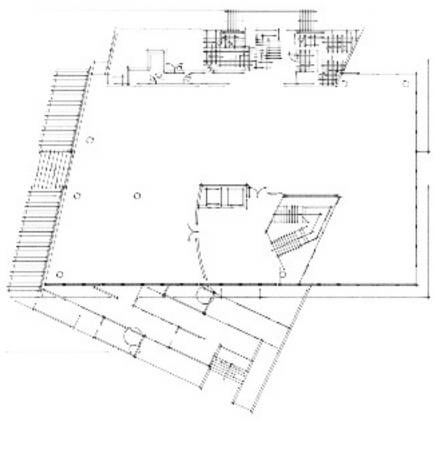


Figure 2. Second Floor Plan

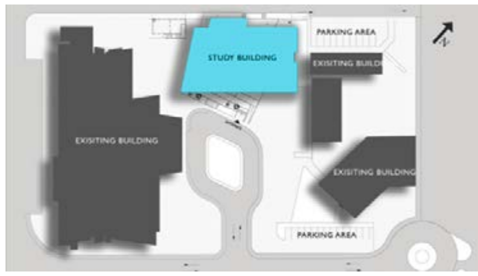


Figure 3. Site Plan

3.2. Abu Dhabi Climate

The city of Abu Dhabi is situated on an island. The climate therefore differs slightly from the hot and arid climate of the UAE in general. From April to October, the average temperature in Abu Dhabi is above the comfort zone range. In January, temperatures reach 27 ºC and begin to gradually increase from there. August is the hottest month with temperature reaching as high as 45 ºC. Diurnal range is around 17 ºC in January and 20 ºC in August. The annual energy demand is around 67000 cooling degree hours. Energy demand peaks in July and August when cooling Degree Hours exceed 10000. Average relative humidity levels range between 51% in May and 70% in November, when humidity levels may exceed 80% at night. The prevailing winds in Abu Dhabi come from the North West, and are characteristically hot, with temperatures ranging between 27˚ C to 38˚ C. [6] In Abu Dhabi, rainfall is very minimal throughout the year. Annual average rainfall does not exceed 100mm. [7]

4. DISCOVERING

The selected organism on which this investigation is based is the desert snail. The desert snail, or *Sphincterochila Boissieri*, is a type of land-based, air-breathing snail that is small in size, weighing around four grams. This type of snail can be found in large numbers in some barren deserts, where temperatures on the ground may reach 70˚C and average annual rainfall is below 100mm. Despite the devastating heat and lack of water, the desert snail succeeds at maintaining its body temperature through different adaptation strategies that are explained in detail below.. Temperatures in and around the body of the snail derived from the experiments discussed in §5.1-5.6 were measured using Copper-constantan thermocouples. Three kinds of measurements were carried out: (1) soil surface temperature was measured by placing the thermocouples directly on the soil surface; (2) snail body temperatures, obtained by inserting the thermocouples through small drilled holes in the shell, and holding them in place with epoxy cement; and (3) air temperature measurements, obtained by placing the thermocouples in the centre of reflective aluminium foil cylinders. [13]

4.1. Withdrawal inside the Shell

The body of the desert snail, as with snails in general, is composed of two main parts: a soft part, which is the live specimen, and the shell.

Retreating inside the shell and avoiding direct solar exposure is considered the main survival mechanism of the desert snail. [4]

4.2. Shell Reflectivity

The habitat in which this organism lives is characterized as being barren. The lack of plant cover greatly reduces opportunities for diffusing or reflecting solar radiation before it reaches the snail. For this reason, heat gain by direct solar radiation is considered one of the main threats to the life of the desert snail.

This lack of reflective and/or diffusive surfaces in the snail's surroundings is compensated for by the high reflectivity of its shell. The desert snail is distinguished from other types of snail by the white colour of the shell. These shiny white shells have the ability to reflect 90% of visible solar radiation, and 95% of infrared radiation. [4]

4.3. Shade

Observations show that the temperature of the soil surface under the snail is less than that of the surrounding environment because this specific spot is shaded by the snail's shell, which extends beyond the actual size of the snail's body. Consequently, less heat is transferred to the body of the snail through conduction. [4]

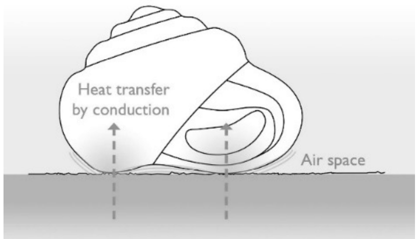
4.4. Air as Insulation

When the snail withdraws inside the shell, it retreats into the upper whorls rather than the larger lower whorl that is in direct contact with the ground. The body of the organism fills only the upper parts of the shell leaving the rest filled with air. This insulates the body of the snail from the ground.

Scientists demonstrated the importance of the air space by measuring the temperature of the body of the snail when the space was filled with air, and comparing this with another reading taken after the space was filled with water. The results showed that air insulation kept the snail five degrees cooler. [13]

Due to its curvature, the shell touches the ground in only a few spots, reducing direct contact between the shell and the ground and leaving a layer of air in between that acts as an insulator (Figure 4).

Figure 4. Airspace insulating the shell from the ground



4.5. Heat Flow and Air Movement

As a result of the different mechanisms mentioned above, temperatures of the components surrounding the snail vary. From highest to lowest they are: parts of soil that are fully exposed to the sun, soil under the snail, air in the largest lowest whorl, air in the upper whorls and air surrounding the snail, as illustrated in Figure 5. Therefore, heat will flow from the higher temperatures to the lowest (surrounding air) with minimum effect on the body of the snail. One might argue that difference will create air movement through the large whorl of the shell.

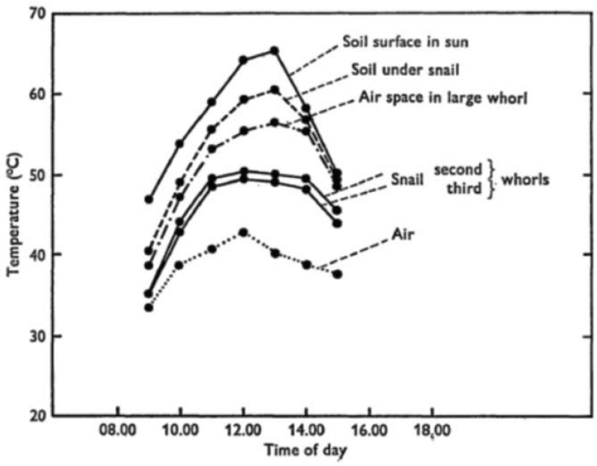


Figure 5. Temperatures recorded in and around a specimen snail [13]

4.6. Evaporative cooling

Experiments show that the weight of a dormant snail changes from day to night. This is because the snail absorbs and stores water at night, and then releases the water through evaporation during the day when the temperature increases. [13] This observations reveals the importance of evaporative cooling in regulating the body temperature of the desert snail.

5. CREATING & EVALUATING

In this section a number of strategies inspired by the desert snail's survival mechanisms are proposed and evaluated. The selected zone for evaluation is the main office space on the second floor of the CERT headquarters building. Based on the information provided by Dewan Architects, the following input parameters were considered:

- Occupancy level: thirty-eight persons
- Level of activity for occupants: sedentary (office work)
- Building envelope materials:

Walls and roof, from outside to inside: aluminum cladding, Rockwool insulation, and concrete and plaster finish (Figure 6). The u-value of the walls and roof is 1.81 W/m²k.

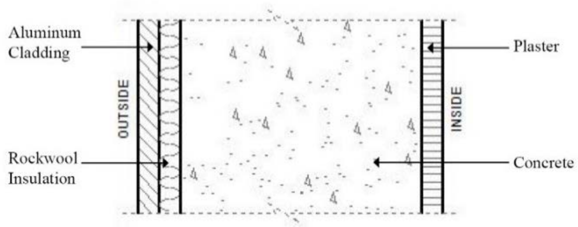


Figure 6. Building envelope materials (Author)

- Glazing: two types of glazing are used in the building: the first, used for the exterior envelope is double-glazed with an air gap; the second is single-glazed, used inside the building as a partition. Both types with aluminum framing.
- Current type of ventilation: fully mechanical system, no operable windows are provided.
- Hours of operation: from 08-1800 during weekdays only.

Results from the Ecotect simulation show that annual cooling loads for the selected zone in the base case is 287989.7 Kwh. (Figure 7). The area of the zone under assessment is 2264.644 m^2, therefore the annual cooling loads is 127.17 kwh/m^2. This is higher than the international energy consumption benchmark, which is approximately 100 kwh/m^2. (200 kwh/m^2 of which 49% is consumed on cooling and heating). [8]

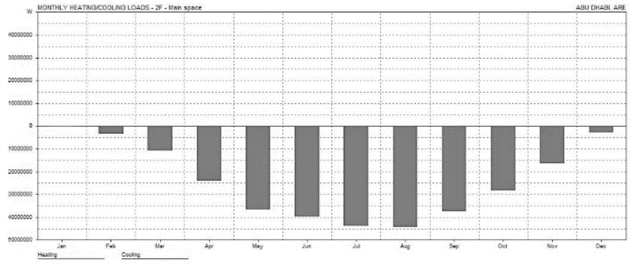


Figure 7. Base case cooling load [5]

5.1. Cool Roof

The roof is the component of the building's envelope that receives the maximum amount of solar radiation in summer, because it is a horizontal surface, exposed to the sun for the entire day; by contrast, for vertical surfaces, exposure changes during the day with some parts shading others, according to the movements of the sun. [9]

Similar to the white reflective shell of the desert snail, the solar reflectivity and thermal emissivity properties, collectively referred to as the Solar Reflectance Index (SRI), of a cool roof, enable it to reduce the heat gain of internal spaces.

The application of cool roof strategies leads to less heat gain, smaller HVAC systems, decreased peak loads, increased thermal comfort levels, and more durability in roof materials. Among the different products available in the market, acrylic based coatings, such as Thermo-shield, are proposed. Thermo-shield is available in the UAE and can be easily sprayed onto existing roofs. Thermo-shield is a highly reflective coating layer composed of acrylic resins filled with ceramic particles. The solar reflectivity of the Thermo-shield coating is around 80%, while thermal emissivity can reach 90%, and its efficiency is comparable to that of a mirror. [4, 9] The effects of cool roofs on thermal comfort and cooling loads were assessed by digital simulation. After changing the reflectivity and emissivity properties of the outer layer of the building envelope in Ecotect, annual cooling loads dropped by 4%, from 287989.7 Kwh to 276131.1 Kwh as illustrated in figure 8.

5.2. Air as an insulator

Enhancing the insulation of the building envelope is a key factor in reduced heat gain and cooling loads. Inspired by the use of air as an insulator by the desert snail, Aerogel insulation was used as a substitute for Rockwool insulation in the form of flexible blankets. Aerogel is an open cell solid material. Because of the method of its preparation, Aerogel has a porosity of 50% or more and a very low density. Some 90 to 95% of Aerogel material is air. For this reason, Aerogel is the lowest density of any solid material, and therefore has a very low thermal conductivity.

Figure 8. Effect of cool roof coating [5]

After enhancing the insulation, annual cooling loads dropped by 19% to 232800.8 Kwh as shown in figure 9.

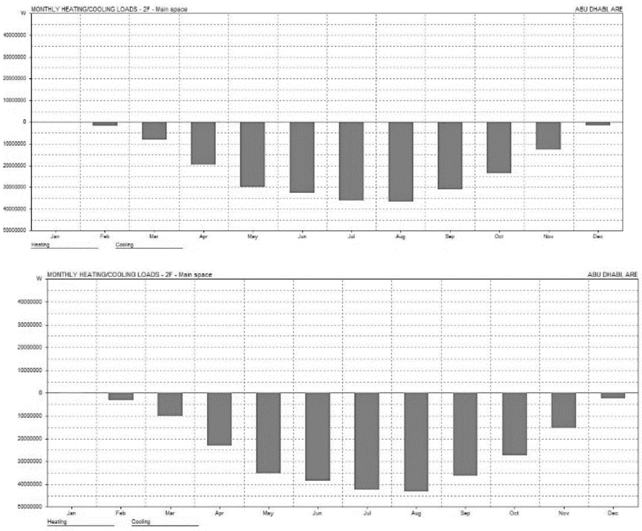


Figure 9. Effect of enhanced insulation [5]

5.3. Layering and Thermal Zones

The desert snail's shell is composed of three whorls with a varying internal temperatures. The temperature is highest in the whorl closest to the soil, and gradually drops towards the smaller, upper whorl where the snail retreats. A similar thermal layering system is proposed here.

Instead of having a single zone that is evenly conditioned, it is proposed to create an intermediate zone separating the main office space from the external environment. This zone is achieved by adding an internal glass partition with a two-metre corridor around it. This intermediate zone is dedicated to circulation and activities other than the sedentary office work that is housed within the internal zone. By adding an intermediate zone, cooling loads in the main zone dropped by 3% from 287989.7 Kwh to 280607.7 Kwh.

5.4. Shading

Design solutions used in the existing building do not use any shading elements for the building or its surroundings. Different shading strategies are proposed below as a way to reduce heat gain.

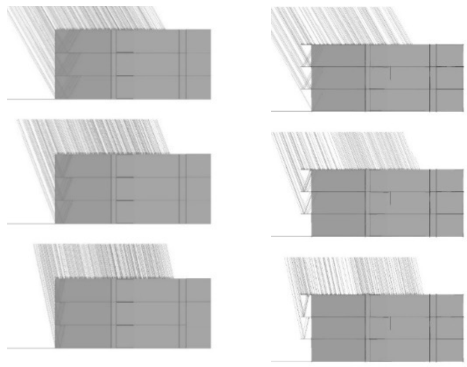
Shading the Building's South-East Façade

The south-east façade is the largest and the most exposed to solar radiation along the vertical surface of the building. Referring back to the natural concept, this study aims to combine different shading strategies in one system by extending the roof and exterior walls of the building to form a shell-like structure and create a continuous architectural element inspired by the spiral growth of the shell of the snail.

Before

After

Figure 10. Solar ray analysis before and



after adding the shading system [6]

In order to assess the efficiency of the shading elements added, solar ray simulation was conducted at three different times as illustrated in figure 10. Results show that adding horizontal shading elements blocks direct sunlight on the southeastern façade and that the average shading percentage during the day will be increased from 48% to 77% (figure 11).

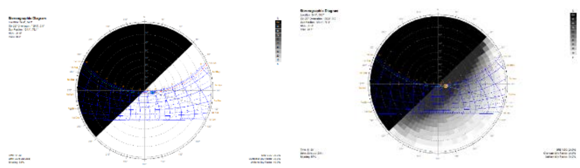


Figure 11. Stereographic diagram showing the shading percentage of the southeastern façade before and after adding the shading system [5]

In addition, Ladybug, an environmental plugin for Grasshopper, was used to evaluate the solar radiation of the south-east façade before and after adding the elements as shown in figures 12 & 13.

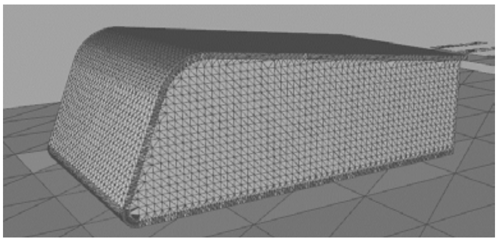


Figure 12. Solar Radiation Analysis before adding the shading system (Ladybug 2015)

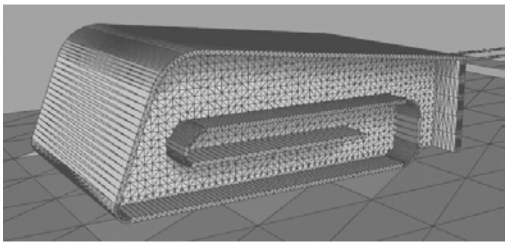


Figure 13. Solar Radiation Analysis After adding the shading system (Ladybug 2015)

Shading the Skylight

A clerestory window is proposed as a substitute for horizontal skylights, which receive the highest level of solar radiation in summer and are therefore better avoided. [7]

The proposed clerestory window not only reduces direct solar exposure (Figure 14); it also enhances daytime lighting levels in the interior space. Figure 15 shows how the daylight factor range dropped from (7.2 – 47.2%) to (4.8 – 44.8%) after a clerestory window was substituted for the horizontal skylight..

Figure 14. Reducing the direct solar exposure (Author 2015)

Shading the Building's Surroundings

Figure 16, which illustrates the shadow range of the buildings in the HCT complex between 8am and 3pm, indicates that the shade created by surrounding buildings is minimal, and that the open spaces around the building are exposed to the sun until after 3pm, at which point the site becomes partially shaded.

In order to create more shaded areas around the buildings, the addition of shading structures is proposed, along with the addition of shading trees. This will help increase thermal comfort levels for pedestrians moving from one building to another, walking from the parking area to the building and vice versa.

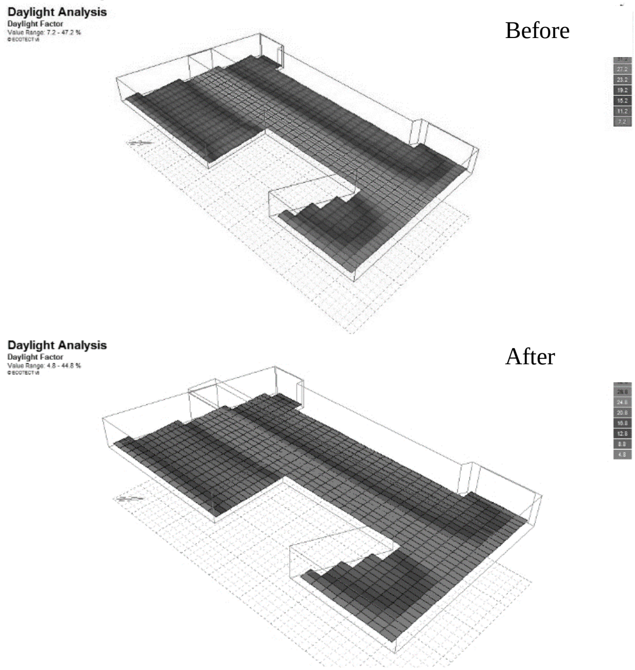


Figure 15. Daylight factor before and after enhancing the skylight design (Author 2015)

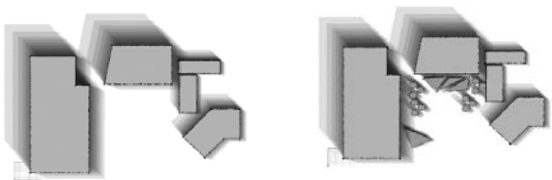


Figure 16. Shadow range of HCT complex from 8 a.m. to 3 p.m. [5]

5.5. Natural Ventilation

The building atrium creates an opportunity to use temperature and pressure differentials to create airflow throughout the building. The proposed natural ventilation system (figure 17) is composed of a south-oriented surface, topped with a glass panel.

When exposed to solar radiation, the dark surface absorbs heat and the glass panel traps it, due to the greenhouse effect, thereby heating the air that exits through the upper opening. This warmer air is then replaced with cooler air that enters through openings provided at each level.

Ecotect simulations show that by providing natural ventilation, cooling loads will drop

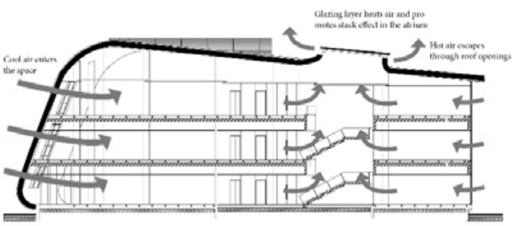


Figure 17. Stack effect ventilation

Significantly in winter, with a 40% drop in December. During the summer months, however, natural ventilation is less effective.

5.6. Evaporative Cooling

According to the data obtained from the Psychrometric chart, evaporative cooling has potential to enhance the thermal comfort levels in buildings in Abu Dhabi. The effect of evaporative cooling peaks in May, when the percentage of comfort hours increases from 4% to 48%. Meanwhile, in January and December evaporative cooling is not effective. The average annual increase in the percentage of comfort hours is approximately 20%. [6]

6. CONCLUSION

In this study, a number of passive cooling strategies inspired by the desert snail's survival mechanisms have been proposed and tested. Results demonstrate that the most effective strategy for cooling is the enhancement of building envelope insulation. With a view to future research, it is suggested that the involvement of a biologist or a specialist in the design process who has the ability to extract solutions to their maximum potential be considered.

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