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ORIGINAL RESEARCH PAPER

Ecosystem Biomimicry: A way to achieve thermal comfort in architecture

H. Abaeian*, R. Madani , A. Bahramian

Department of Architecture, University of Isfahan Art, Isfahan, Iran

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ABSTRACT: The strategies to reduce the consumption of non-renewable energies in buildings are becoming increasingly important. In the meantime, nature-inspired approaches have emerged as a new strategy to achieve thermal comfort in the interiors. However, the use of these approaches in architecture and buildings requires a proper understanding regarding the features of ecosystems. Although acquiring this knowledge requires a high degree of familiarity with the fields such as biology and environmental science, review of achievements made by the use of these features could facilitate the understanding of ecomimicry processes and thereby contribute to environmental sustainability in buildings. In other words, this paper concerns the relationship between these features and the thermal comfort inside the building. Biomimicry is an approach to innovation that seeks sustainable solutions to human challenges by emulating nature's time-tested patterns and strategies. The objective of this paper is to use such review to provide an approach to the use of natural features for achieving thermal comfort in the buildings of hot and dry climates. In this review, the successful examples are analyzed to identify and examine the principles that influence the thermal comfort in both building and urban levels. The results show that the three elements of water, wind, sun are the effective natural resources that must be utilized in the design in a way proportional and consistent with the natural features. In addition, functional features of ecosystem can be of value only in the presence of a processual relationship between them.

KEYWORDS: *Biomimicry; environmental sustainability; Natural ecosystems; Sustainable architecture; Thermal comfort*

INTRODUCTION

Currently, human settlements rely on fossil fuels to meet heating, transportation and energy needs. This reliance is the major cause of pollution and exacerbation of climate change. Building sector is responsible for one third of the world's carbon dioxide emissions (IEA, 2012). This sector is also involved with lowered quality of water, air, soil and human health. In many hot and dry regions, half or more of the energy consumption is for air conditioning. Cooling consumes more energy than heating, so in semi-arid developing countries, there will be a high pressure on energy resources for meeting future demands, unless new measures are introduced (Koch-Nielsen, 2013). Therefore, presenting novel solutions for passive cooling in this climate seems necessary. On this basis, the purpose of this study is to identify successful architectural solutions for achieving thermal comfort in hot climates with the use of passive methods; solutions that can adapt to problems such as pollution, drought and climate change in both building and urban levels. To solve these problems, architects have developed successful models inspired by natural ecosystems for accessing renewable energies (Zari and Storey, 2007). Although architects can use many aspects of ecosystems to assess and explore the methods of building, those features that can offer flexibility against climate changes are far more effective. These features are regarded as instruments for optimized use of renewable energies (and therefore optimized design of building) and can vary with the environmental conditions (Zari, 2010).

But what natural features could be regarded as

*Corresponding Author Email: *Abaeianhamid@yahoo.com*
Tel.: +9891 3266 5824

such? How can these features make conditions inside buildings and urban environment more desirable? And most important of all, inspiration from which natural feature is more effective for achieving the desired thermal comfort?

To answer these questions, we first assess the features in natural ecosystems and then analyze two successful cases to better understand these features. One way to reduce the consumption of fossil fuel is to use passive solutions. The use of passive solutions is also an effective approach for providing high quality indoor conditions with advantages such as the use of natural energy and abundance of available resources. Several studies show that sustainable thermal comfort in buildings is achieved when the main focus of design is on energy-efficiency (Mlecnik *et al*., 2012). Also, new studies show that environmental quality of indoors not only affects the convenience of spatial realization but is also a factor for increasing the efficiency and health of indoor employees (Aries *et al*., 2015; Fisk and Rosenfeld, 1997; Singh *et al*., 2010). But matching the features of a passive design with the features of a healthy environment seems to be difficult (Kellert *et al*., 2011; Graham, 2009). One way to achieve such match is to design using inspirations taking from natural ecosystems. Studies suggest that mimicking or taking inspirations from natural ecosystems has a great potential for reducing human-induced destructive effects on natural environment and achieving environmental sustainability (Zari, 2007; 2010). Many researchers believe that mimicking the ecosystem is an integral part of bio mimicry (Benyus, 1997; Vincent *et al*., 2006), which sometimes has been described with Eco mimicry (Lourenci *et al*., 2004).

Testing and using the concepts of natural ecosystems can improve the design and also present solutions for other fields. In this context, several researchers have attempted to identify and understand the methods of incorporating the ecosystem into architectural design (Bejan, 2000; McHarg, 2010; Kibert *et al*., 2003; McDonough and Braungart, 2010; Graham, 2009; Van der Ryn and Pena, 2002). Also many ecologists have assessed and analyzed applications of ecosystems and the use of their functions for human life (Daily *et al*., 2000; Alcamo, *et al*., 2003; de Groot, *et al*., 2000).

The present study seeks to assess the ecosystemic features that can be used in architecture by analyzing the successful examples in this regard.

MATERIALS AND METHODS

This study first assesses the natural features that can be used in architecture. Then these features are studied in specific categories. In the next step, to better understand these features, the successful examples of use of these features are analyzed. In the end, the relationship between thermal comfort and the manner of using of these features is investigated. Considering that research objective is to present a solution for urban environments and buildings located in hot and dry regions, one successful example is selected for urban level and the other one is selected for building level. The study population consists of case examples built in semi-arid climate, and research objective is pursued by assessing one project dedicated to a single building and one project dedicated to an urban space.

Ecosystem

Ecomimicry mean identification of natural elements and features for obtaining the results existing in the nature in the design area (Maglic, 2012). Overall, inspiration from natural ecosystems can be taken in two levels: Functional level (what do they do?) and processual level (how they do it?) (Zari, 2012; 2015a). To better understand the processual level, Table 1 indicates a number of ecosystem-inspired architectural solutions in this level. This Table can reflect how processes can be combined for the construction of an environment. The use of these solutions can improve the sustainability of the design (Zari and Storey, 2007; 2010; Reed, 2007; McDonough and Braungart, 2010).

Like processual level, functional level is composed of a series of theoretical goals and concepts, but specific methods for achieving these goals can include a wider range of architectural models and tools. Ecomimicry at functional level allows the designer to know which aspects of the local area he must comply with so that the designed structure would be consistent with its surrounding environment (Zari, 2015a; Alcamo *et al*., 2003; Daily, *et al*., 2000).

Therefore, mimicry of features of a natural ecosystem has two forms: mimicry of general and distinctive features of natural ecosystems (for improving optimality, adaptability, etc.) based on how processes take place. These features are also called processual features (Zari, 2015b). The second category is the mimicry of function of the ecosystems. In other words, mimicking what a natural ecosystems does (e.g. carbon adsorption, air purification, power generation, the deal

Table 1: Ecosystem-inspired processual solutions for architectural design of indoors (Zari, 2010; 2015a)

Process strategies in ecosystem biomimicry		Existing related design techniques	Climate change implications
1. Dependent on abundant Renewable energies	Source energy from current sunlight, or other renewable sources	Active and passive solar design	Reduction of GHG emissions increased energy effectiveness
2. Optimization structures	Cycle matter and transform energy effectively	Industrial ecology; construction ecology; design for deconstruction and reuse; cradle-to-cradle design; permaculture; general engineering	Reduced need for mining/ growing/production of new materials and energy; reduced use of energy and materials; and reduced waste
3. Dependent upon and responsive to local condition	Source and use materials locally and use local abundances	Permaculture	Reduced transport-related GHG emissions
4. diverse in relationships and information	Increase diversity to increase resilience	Participatory design; integrated design methods; eco-revelatory design; ecological design	More robust built environment and community able to adapt to climate change. Decisions based on a broader knowledge base are likely to be more sustainable (Wahl and Baxter, 2008)
5. create conditions favourable to sustainable life	Production and functioning should be environmentally benign.	Green chemistry; life-cycle analysis; carbon balance; regenerative development; cradle-to-cradle design;	Healthier ecosystems mean better life-support systems for humans and greater potential to adapt as the climate changes
6. adapt and evolve at different levels	Mechanisms for self-organizing	flexible design methods	Allow for rapid, effective and participatory change.

Table 2: Ecosystem-inspired functions for architectural design (Zari and Storey, 2007; Zari, 2010; 2012)

Ecosystem functions for the built environment to mimic		Existing related design techniques/technologies	Climate change implications
1. Provisioning services: food, materials, fuel/ energy, fresh water	Development should provide food, raw materials for future developments and fuel	Green roofs; vertical farms, recycling and reuse, renewable energy, rain water collection; grey/black water recycling	More self-reliant
2. Climate regulation, prevention of disturbance and moderation of extremes	Development should prevent disturbance and moderate extremes such as wind/wave forces, erosion and floods/ droughts for surrounding ecosystems.	Storage of carbon in building structure; green roofs	Reduced rate of global warming
3. Provision of habitat	Development should actively contribute to soil formation and the renewal of fertility	Black recycling and reuse techniques/greywater recycling;	Healthy soil means greater potential for healthy biomass and food production and Therefore human health and resilience.

absorbing, disposing and storage of heat or coolth, absorption or disposal of humidity, light, etc. (Zari, 2012). In the next sections, these features are assessed in two case examples.

Melbourne City Council House (CH_2)

After examining the features of ecosystems that can be mimicked for architectural applications, we discuss the building of Melbourne City Council House (CH_2), which is one of the examples of sustainable architecture and the efficient use of clean energy for interiors (Zandieh and Nikkhah, 2015). Sustainable technologies can be observed in every aspect and level of this 10-storey building (Fig. 1). The presence of underground water treatment facility, the phase change material used for cooling, the automatic windows used for heat purging at night, the shades that adjust to sunlight direction, and even the plant pots used on facade, are all symbols of purposeful and fresh thinking behind the design (Zari, 2015b).

Although most of the principles employed in this building (e.g. the use of heat storage for cooling, use of plants for light control, use of glass to trap heat in winter days, etc.) are not new, the use of these principles in such a comprehensive and interconnected way is unprecedented in Australia. CH_2 building is a clear example of how a building can comply with financial, social, and environmental standards (Tan, 2007; Aye and Fuller, 2012; Paevere *et al*., 2008; Zari, 2012; 2015a). To properly analyze this building, its daytime and nighttime functional process in both summer and winter will be discussed.

Summer

In CH2, more resources has been spent on the cooling system than on the heating system, in order to with the significant amounts of heat constantly generated by electronics and human activity. The building's heat generating systems has been designed to make the best use of available heat (Tan, 2007; Aye and Fuller, 2012; Paevere *et al*., 2008), as a result, much of the building's energy use is for cooling. Fig. 2 shows the building's cooling process in summer.

Summer–daytime

During warm days, the water stored in the winter and frozen by compressor passes through the entire building and the chillers installed on the roof of each floor. This flow of water generates a gentle coolth of 18 °C in the workspace. This method is used in place of the traditional method of using a fan to blow the cold air into the building (Aye and Fuller, 2012; Paevere *et al*., 2008).

Fig. 1: CH_2 building: right: spray of water to cool the southern facade, middle: A view of the exhaust flue (North), left: Western view (Pearce, 2014)

In each floor, the warm air rises up toward the ceiling, lose its heat to the cold water pipes, and then returns to the space (Fig. 4). In addition, the fresh air enters into the raised floor through the southern facade (located in the shadow) and then passes into the space through the vents embedded in the floor. In each floor, hot air is also released through suspended ceilings leading to northern vents (exposed to sunlight), where dark colored ducts in the terrace space absorb the thermal energy of sunlight and suck the air upward. At the top of the building, the resulting strong air flow moves turbines to produce power. The following Fig. 3 shows a horizontal cross-section of northern terraces and air ducts.

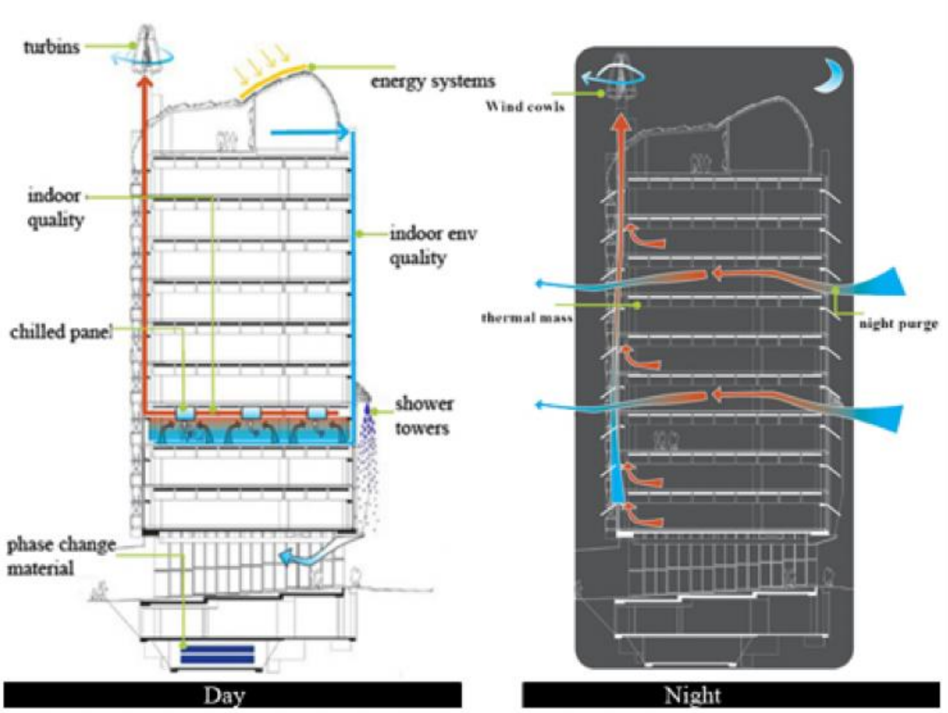

Fig. 2: daytime and nighttime functional process of CH2 building in summer, the author based on (Tan, 2007)

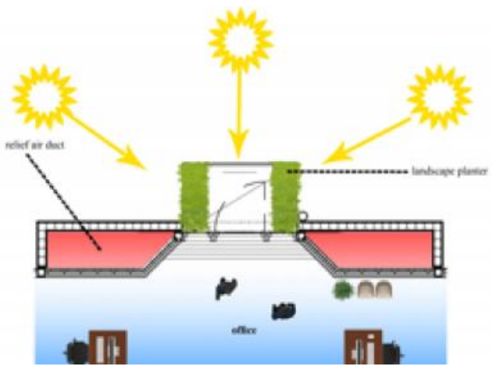

Fig. 3: functional diagram of terrace and office space, and channeling of hot air through air ducts

The green roof of the building creates a shaded space with a lower temperature, where the recycled water passes through to reach 5 light-colored sprinklers spraying the water downward from a height of 17 meters, which leads to evaporative cooling of commercial spaces at ground floor. In addition, the presence of louvres made of recycled wood in the western facade protects the building against the heating induced by direct sunlight (Fig. 5). These louvres can be electrically opened and closed and the required electrical energy is provided by solar panels on the roof.

Moreover, the presence of plants creates a cool and humid atmosphere in the terrace, and also shades the indoors against sunlight (Fig. 6).

Summer/ nighttime

During night, the building is cooled through natural ventilation by windows getting open and closed automatically based on inputs of wind, rain and temperature sensors. Open windows let in fresh and cool night air, which subsequently cools the 180 mm thick prefabricated concrete ceilings. The high thermal capacity of concrete material allows this ceiling to store

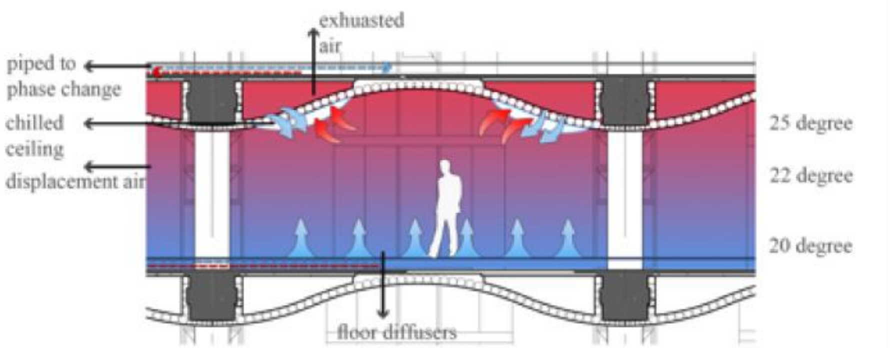

Fig. 4: functional diagram of internal air cooling by the chillers embedded in the ceilings (Tan, 2007)

Fig. 5: CH_2 building: right: northern view (air suction ducts) - middle: the roof structure – left: light-colored vents on the southern façade (Meinhold, 2009; Pearce, 2014).

Fig. 6: the interior space of the building: right: the northern terraces - middle: office units - left: windows used for ventilation (Meinhold, 2009)

the nightly coolth and release it into the room during the day. In summer, this mechanism triggers a 14% decrease in the cooling load that need to be addressed mechanically (Fig. 2) (Aye and Fuller, 2012; Paevere *et al*., 2008).

Water management

In the CH_2 building, some of the wastewater is treated in the treatment unit of the building. This unit filters the wastewater and sends the solid part to the sewage network. Then, a micro-filter system treats the resulting water to a quality sufficient for non-drinking use. This recycling provides a portion of water required in cooling network, engine room, toilet siphons, facilities, fountains, and for watering the plants (Fig. 7). The building also stores a considerable volume of water by collecting the rainwater. Overall, these process lead to recycling and reuse of about 100 thousand liters of water. Part of the recycled water is used for watering the vertical gardens positioned across the northern facade of the building. These gardens have been designed to act as a barrier against intense sunlight and to provide fresh air for indoors (Aye and Fuller, 2012; Paevere *et al*., 2008).

At each floor, a number of purposefully designed plant pots are fixed to the balcony. Supported by a mesh of stainless steel, tendrils planted in these pots climb upward where they meet the tendrils of upper floor growing on the same path (Figs. 3 and 6).

Winter: during cold months, the wooden louvers of the western façade open up to let in the direct sunlight and thereby generate warmth by inducing a greenhouse effect in the building. Fig. 8 provides a clearer picture

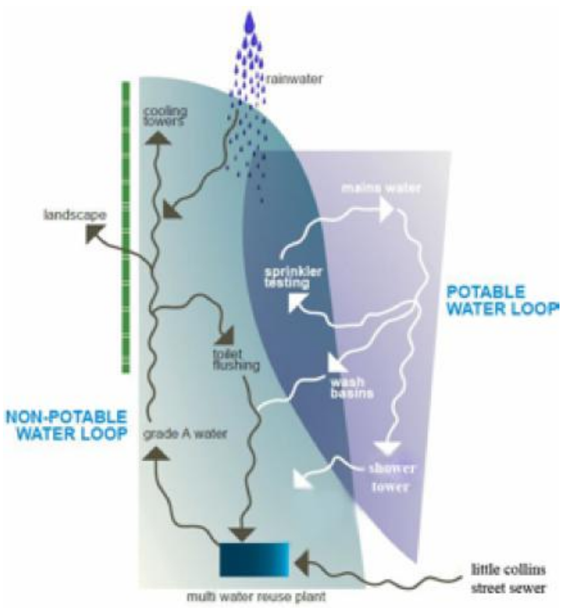

Fig. 7: water recycling in CH_2 buildings, the author based on (Tan, 2007)

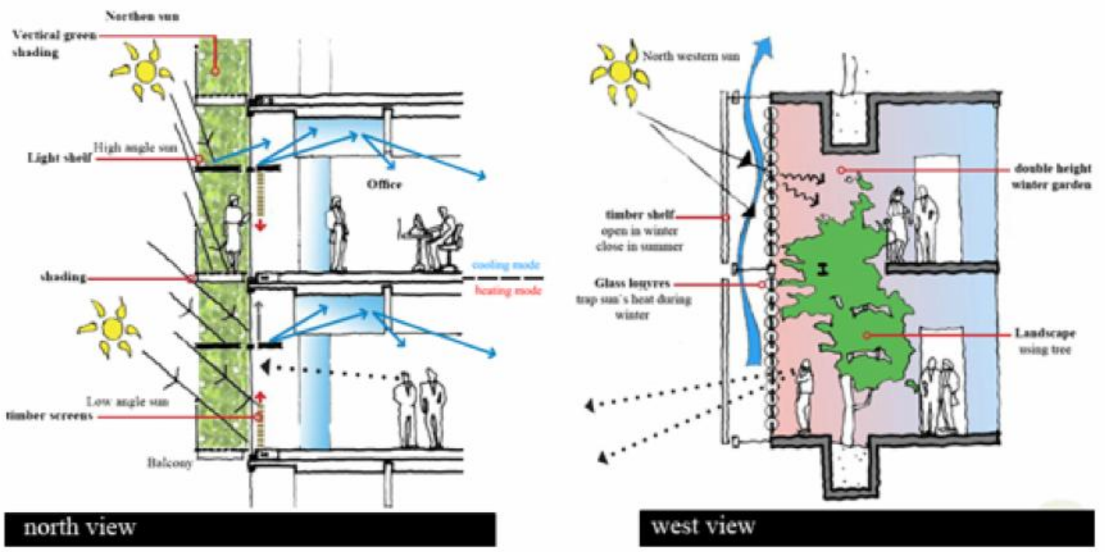

Fig. 8: temperature and sunlight regulation in the northern and western envelop during the course of a year (Tan, 2007)

of functional process in northern and northwestern side of building envelop during the course of a year. The construction of this building costed 22.2% more than a conventional building, but the 10.1% higher energy efficiency reimbursed the extra cost after 5 to 7 years. Comparing this building with the building in the neighboring lot shows that the new design has led to 82% saving in electricity consumption, 87% saving in gas consumption, 72% saving in water consumption, and 4.2% increase in the productivity of employees (Zandieh and Nikkhah, 2015; Tan, 2007; Aye and Fuller, 2012; Paevere *et al*., 2008). Another estimation shows that the savings made as a result of environmental features of this building can be expected to cover any extra cost of construction (in comparison to a similar but conventionally designed building) during the 10 years of operation (Zari, 2015a). This suggests that taking inspiration from the nature or bio mimicry is a viable approach for dealing with changes in environmental conditions while providing an atmosphere in accordance with the standards of human environment, and should be given preference in technology oriented designs.

Zira complex

Another successful example ecomimicry is the Zira Island masterplan designed by the Bjarke Architecture Group (BIG) headed by Bjarke Ingels (Fig. 9).

This island is located in the crescent-shaped bay of Azerbaijan's capital Baku in the Caspian Sea coastline. Although the objective of designing a zero energy complex as big as 1 million square meters seem to be impossible, in this project, this aim was achieved by taking inspiration from natural ecosystems. The theme of this project is inspired by the legend of presence of 7 historical mountains in this area (Fig. 9), but in this design, comfort is provided through coordination with the surrounding environment. The spaces of this project consist of 7 artificial mountains housing and surrounded by living and leisure spaces provided for island residents. But what is relevant to this study is the previous condition of this island and the manner of devising a design such environment. Zira Island is devoid of any plant, water or other resources and can be generally described as a desert (Bjarke, 2009; Rukmane-Poèa and Krastiòð, 2011). For this reason, the general theme of the design is to create an independent ecosystem capable of meeting its own needs while maintaining harmony with its environment. In general, the overall form of the project has been shaped based on the elements of wind, water and sun, which will be discussed in the following.

The overall process in the Zira Island

Wind energy produced by turbines installed on the coast of the Caspian Sea power a number of desalination units that filter the salt from sea water and turn it into fresh water ready for human consumption. This water is then used for heating and cooling the buildings. All the wastewater returns to the environment to provide the island's plant water requirements. In addition to wastewater, storm water is also collected and used for watering the plant life around the island. When extracting the water suitable for human use, the waste materials are filtered and collected, and then crushed and used as nutrients for plants. Solar heaters and photovoltaic panels installed on the façade and roofs of the buildings are used for energy production. Using all of these elements together makes the island an easily habitable, independent, and sustainable ecosystem.

Fig. 9: A view of the Zira Island designed based on natural ecosystems (BIG, 2010)

The process considered in this design is illustrated in Fig. 10.

This process is the result of consideration and coordination of three elements of water, wind and sun (Fig. 11) based on the existing features and terrain of the region. Thus, for better identification and analysis of this project, the designer's approach to these three elements will be discussed.

Wind: One of the island's main features is its windy location. During the design, the element of wind has been approached from two angles: 1) the use of wind turbines installed along the coast to provide the island's required energy; 2) the simulation of wind flow within the island and around the seven artificial mountains. By identifying the microclimates created by the 7 artificial mountains, this simulation provides a suitable background for placement of spaces (Fig. 10). Thus, the required spaces have been located based on the wind speed obtained from the simulated model. In areas where wind speed is undesirably high, compact patches of green spaces and trees have been designed to reduce the wind speed; and in areas where wind speed is desirable, residential and recreational spaces have been predicted.

Water: In this design, sea water treated by desalination systems is used to meet the island's water requirements. Also all water used on the island is collected and recycled along with the rainwater. After treatment, the water is reused for watering the trees and green spaces. Also, the salts and residues obtained from treatment are returned to the soil to fertilize the island.

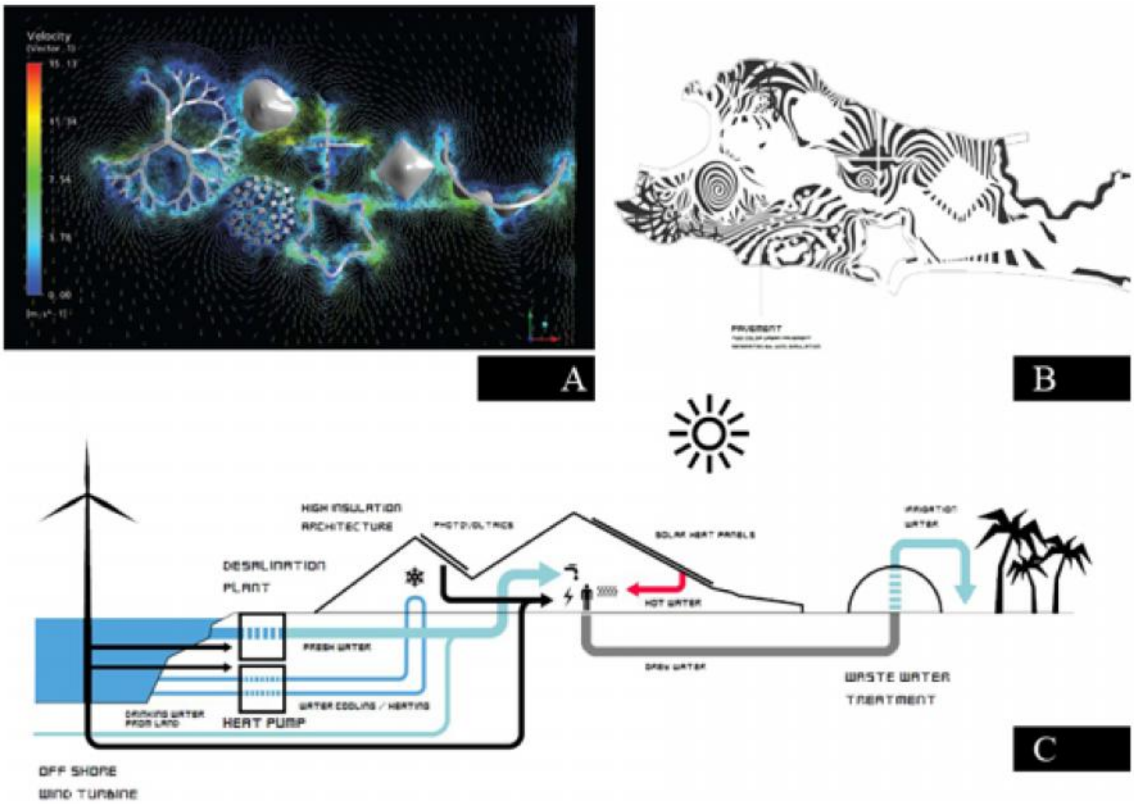

Fig. 10: A: simulation of wind flow for the Zira island –B: Pattern created in the island due to microclimate resulting from the presence of 7 artificial mountains -C: functional process considered in the new design of Zira Island (BIG, 2010).

Sun: buildings of the Island can be heated and cooled by the pipes crossing the shores of the Caspian Sea. Solar panels and photovoltaic systems installed on façades and roofs of the buildings are used to provide a big portion of warm water and also power the swimming pools and water parks.

The constant fertilization and irrigation will create a lush environment in a tropical area. Also, wind is directed toward living and leisure spaces to provide a desirable flow of fresh air for residents. All these have been created only with the help of ecological features.

RESULTS AND DISCUSSION

The natural features that can be mimicked in architectural applications to achieve thermal comfort can be generally divided into two groups of functional and processual.

The relationship of these features is of vital importance for achieving the desired result. Functional features provide the designer with an approach to solve a certain problem in a certain area; but the use of processual features leads to extension of a continuum among multiple functional features, and thereby ensures the stability and sustainability of the entire building system. Diagram of Fig. 12 shows how functional features of an ecosystem are linked to form an ecosystemic process in the case examples. There are also other links within this diagram, but in this case,

Fig. 11: the use of natural resources, wind, sun and water, to achieve energy optimization purposes (BIG, 2010)

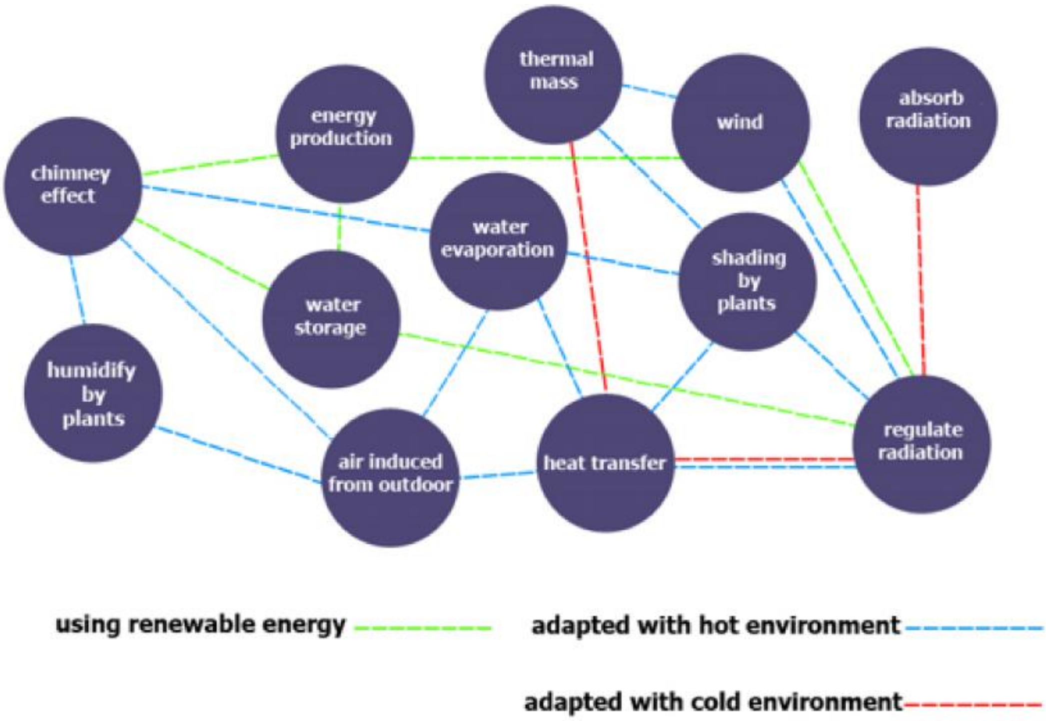

Fig. 12: functional and processual features of case examples

only the issues relating to environmental sustainability and comfort conditions are of interest. The presence of is a mutual relationship among several functions creates complex intra-system relationships and ultimately leads to environmental sustainability.

Therefore, management of three natural factors of sun, wind and water by taking inspiration from natural cycles can lead to provision of thermal comfort and reduction of energy consumption in the buildings. Although the prescribed systems will vary with geography, terrain, climate and time, the attention paid to the natural factors and their interaction in the ecosystem will certainly affect the quality of final outcome.

Also, according to the examined case examples, one of the existing potentials in taking inspiration from natural ecosystems is the ability to integrate with sustainable construction methods that are not generally biomimetic in a variety of different temporal and spatial conditions. Hence, mimicking the natural ecosystems is a viable approach for construction of built and urban spaces that are to be in harmony with their environment and adaptable to the environmental changes; because the basic constituting elements of such approach are the environmental components, which adapt to any change in climate and its ensuing effects. When followed and implemented properly, such approach can even lead to emergence of a green city out of a desert without the use of expensive technologies; an event that the step after creating a favorable conditions for the interior spaces.

CONCLUSION

According to the aforementioned material, the three following suggestions are presented to achieve sustainable architecture:

1. Using existing processes in natural resources: natural elements found in the natural environment are the best and most sustainable resources to achieve the goals coming in the buildings. In the meantime, whatever natural processes in the design process to be used instead of the effect of natural resource, achieving sustainable architecture will be realized. Processes, such as pressure difference, evaporation and natural ventilation, etc., which if there are appropriate capabilities in design, can have stable and enduring impact on the building. In other words, instead of using sunlight to create an atmosphere as the greenhouse, and with the purpose of use in the event of the year, the impact of solar radiation in pressure differences in building body and creating natural ventilation, can be used.
2. The use of processes dependent upon each other: like structures found in nature, the use of complex structures with a dual relationship with each other increases structural stability in the whole year.
3. The air-conditioning channels: In hot and dry climates, use of natural ventilation with the use of sun, wind and water consumed by residents after the treatment process is effective in reducing the air conditioning channels. Vertical ducts exposed to sunlight cause the pressure difference between the bottom and top points of the channel as well as creating air flow. Enjoying the process of evaporation of water leads to enhance the effect.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript

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