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Towards a Platform of Investigative Tools for Biomimicry as a New Approach for Energy-Efficient Building Design

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Abstract: Major problems worldwide are environmental concern and energy shortage along with the high consumption of energy in buildings and the lack of sources. Buildings are the most intensive energy consumers, and account for 40% of worldwide energy use, which is much more than transportation. In next 25 years, CO_2 emissions from buildings are projected to grow faster than in other sectors. Thus, architects must attempt to find solutions for managing buildings energy consumption. One of new innovative approaches is Biomimicry, which is defined as the applied science that derives inspiration for solutions to human problems through the study of natural designs' principles. Although biomimicry is considered to be a new approach for achieving sustainable architecture, but there is still not enough access for architects to make use of it, especially to implement biomimetic design strategy in architectural project. The main objective of this paper is to raise awareness of architects making use of biomimetic strategies with better accessible facility. We propose to create the tool setting relationship to formalize and bridge between biological and architectural knowledge, along with investigative tools to investigate the ability of reducing energy consumption by applying the biomimetic strategies on efficient-energy building design. This article hypothetically proposes an investigative tool based on Bayesian networks for testing the rapid result of choices from natural devices according to specific multi-criteria requirements in each case study.

Keywords: biomimicry; architectural design; energy efficiency; sustainability; data analysis; Bayesian network

1. Introduction

The energy consumed through using buildings and producing building materials forms a significant portion of overall energy consumption in affluent societies today [1]. We are nowadays facing two major problems related to energy consumption. One is the depletion of energy resources and mineral raw material and another, the increase of various types of pollution that cause what is commonly called global warming [2]. Indeed, the release of the greenhouse effect results primarily from the burning of fossil fuels, whose reserves are falling dramatically, and are used in the building industry to ensure both comfort and performance of materials and systems composed. Depletion of mineral resources in the construction sector is, by volume, the consumer faces a waste accumulation of the problem that is growing and that today is increasingly difficult to manage [3]. Buildings, because their heating consumption in industrialized countries uses more than half of energy, is therefore the biggest polluter [4]. Saving energy in the building (in both its consumption and at its completion) would effectively contribute to the grip of the decrease of the problems cited. Energy flows through buildings need to be better structured and managed, and their occupants need to change existing patterns of behavior [5]. There are several reasons why this prospect is challenging. The way buildings come into being is a complex and adversarial affair driven by economic considerations and the avoidance of risk, which favor incremental improvements of established designs. Many works are incurred in responding to these questions, either by improving the performance envelopes [6], HVAC systems [7], energy production [8], but also to promote reuse in architecture and well reduce the waste of natural resources [9]. We propose in this work to question biomimicry as a source of inspiration for architects and builders in order to provide the solutions that nature can find: by integrating its environment and optimizing energy and material necessary for its survival. Biomimicry could be used as a tool for energy-efficient building design aiming to achieve reducing energy consumption by innovative design and sustainable energy generation without negatively impacting the natural environment. By looking at the living world, there may be organisms or systems that can be mimicked to create and maintain clean energy generation or sustainable technologies [10]. Additionally, biomimicry provides the means to determine achievable goals for development based on physical reality. It also provides the method to achieve these goals, and at the same time it points to countless examples that can be emulated. Although there are many smart solutions inspired by natural phenomena, it is not always clear how analogies were abstracted from the biological process. Life's principle could provide specific design ideas (strategies) and metric to measure whether the proposed design indeed meets nature sustainability principles [11]. However, some of the principles are general and their application in engineering design is neither clear nor straightforward. In addition, it is unclear how the life principles were revealed and how to search for new ones [12]. Thus, we propose to facilitate a tool for biomimetic design strategies to set objectives and metrics that can be used for deciding which of the biomimetic ideas should be further elaborated. In addition, we provide information as to what requirements (multi-criteria) are appropriate to explore the chosen biomimetic ideas. Finally, it will conclude with the tool setting relationship knowledge between biology and architecture, applied to biomimetic strategies and the design of energy-efficient buildings. This tool could provide to search suitable principles in nature in an applicable way for architects to meet specificity in each project implementation.

2. Overview of Energy-Efficient Building Design

When we talk about energy conservation, it is customary to say that the design process is done in three phases [13]. Indeed, one of the key approaches to low-energy design is to invest in the building's form and enclosure. The first is to reduce energy needs by carefully designing the building envelope so that the heating, cooling and lighting loads are reduced. The second is to offset the remaining needs for efficient systems and appliances, and the third aims to make the most of resources, which means free energy that are available in the occupation site. These three phases can be reduced considerably the energy consumption effectively for the new building without user's impact (an understanding of building occupancy and activities can lead to building designs that can save energy, reduce cost and improve occupant comfort and workplace performance) [14]. Nevertheless, if we want to concern deeper it is necessary to consider the building throughout its life cycle, that means to reflect its operations and maintenances, refer to its demolition. These phases according to their support during the design process will require more or less energy. We must also add to the embodied energy necessary for its implementation, its rehabilitation and demolition. This is a global vision that provides an essential place in the energy criterion (of all kinds of uses) among other architectural criteria we must have. In view of the crisis of the source that the world is currently living [15], is another point to add. This aspect highlights the need to optimize the use of the material to see the establishment of a re-employment system. (If one want to look more of what all the nature has).

2.1. Reduce Energy Needs

Humans have always taken advantage of local conditions by offering a vernacular architecture, which for centuries has operated with means often-simple characteristics and natural resources of their environment. If we observe how these architectures are able to give their best characteristics for different environments and response to specific needs such as the Tuareg tent, Inuit igloos (Figure 1a) and troglodyte Ethiopian church [3]. Gradually, as technology is developed, the architectures become more sophisticated to meet the needs and comforts of its users regardless of the performance of the envelope to environmental impact or approach overall energy needs to go through the awareness of the essential elements to a good architectural design. Ventilation and air heating systems have, for some time [3], solved only the comforts of requirements by increasing their powers regardless of the service, incurring costs to environmental impact.

Based on this observation, the French new energy performance of new building regulation—aka RT2012 [16] today imposes through bioclimatic needs (as a tool). This new regulation aims to reach low energy consumption for all new building along with bioclimatic design principles, which aim at the construction of buildings that are in harmony with the natural surroundings and local climate, ensuring conditions of thermal comfort inside (Figure 1b). The steps to follow to achieve this goal through a bioclimatic design of the project: (1) The building as a natural solar collector in winter: maximizing the glazed surfaces facing south to take advantage of free solar gain and minimize the glass surfaces facing north, where heat losses are higher than solar gain; (2) The building serving as a heat trap: optimizing the compactness of the project, to reduce the dissipating surface; (3) The building serving as a heat storage: increasing the insulation thickness; (4) Dealing with thermal bridges by providing an exterior insulation, or by setting up the thermal bridge breakers; (5) The building serving as a natural cooling trap/storage: Sun protection, natural ventilation; (6) Offering quality doors and windows (triple glazing, thermally optimized) and etc.

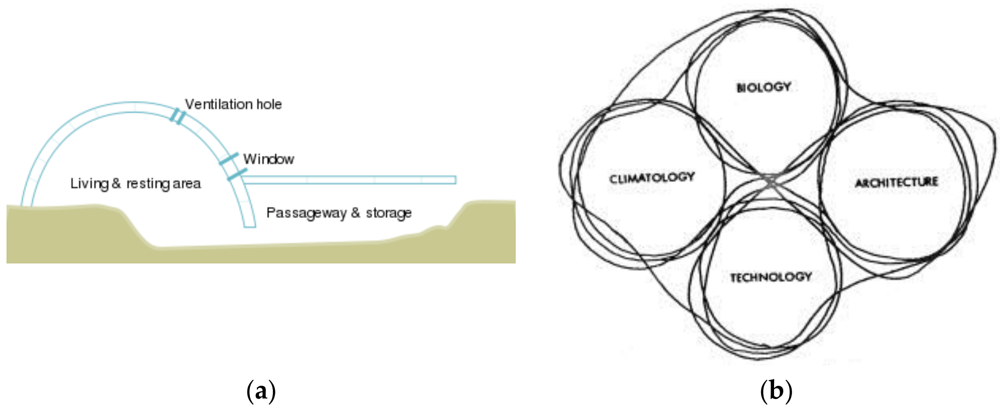


Figure 1. (**a**) Igloo construction, with the compact of snow to insulate the interior where is warmed by body heat alone [17]; (**b**) Interlocking fields: Bioclimatic Design [18].

2.2. Efficient Heating, Ventilation and Air Conditioning Systems (HVAC)

Once energy requirements are reduced through a bioclimatic design, a choice of high-performance materials (insulation, glazing, etc.) and power systems (HVAC and lighting) will be lower and so it will economize over the long term (investment as consumption). Much of the French building stock, for example, is renewing its air by natural ventilation (opening windows, air infiltration related to leaks, etc.). This ventilation mode generates significant heat loss and is not adapted to the requirements by reducing current energy consumption; this is often due to the difficulty to master this type of ventilation. Therefore, regulation RT 2012 [16] geared more toward developers of active techniques (VMC single stream or dual stream) to ensure efficient and controlled ventilation but at what price? In the best case, a mixed choice is offered as is practiced in the building of the house in Alsace region of France in which the proposed solution is a natural ventilation system assisted and controlled (VNAC) [16]. Depending on the climate, it is possible to reduce considerably view to cancel the heating or cooling needs, just by proper design such as "PassiveHous" project [19] and super insulated envelope and super tight, or alternative constructions "Earthship" Michael Raynolds California [20], which in addition to excelling in the art of reuse of materials has inspired systems integration of vernacular architecture as a greenhouse associated with high inertia heating and adiabatic cooling, to reduce strongly the need for active systems.

2.3. Production of Sustainable Energy

In the best case, after we carefully design buildings with a high-performance envelope, efficient HVAC and lighting systems. It is customary to offer high efficiency power generation systems and promote those using renewable energy (solar panels, heat exchangers, natural wind). It has been proved that, apart from the proven performance systems such as photovoltaic for energy production, for example, its production and processing end of life is disastrous from the ecological point of view [21] do realize through literature and examples of built works we know today, to construct buildings those consume little or zero energy. However, we realize that also includes proposed solutions to achieve are not completely harmless and at the end the energy balance of the building, although efficient in terms of consumption, is not so neutral as that. Indeed, the choice of high performance insulation that is not bio-sourced, therefore difficult to recyclable, and for a heating system or production of active energy has an impact on the environment. Therefore, the question we can ask ourselves is: What can we do to promote the use of less harmful and more passive solutions for the environment without affecting the performance in terms of building consumption? Added to this, is the question of life cycle [22] building energy costs by embodied energy implemented to produce the materials and systems that make up these buildings, their maintenances and end of life treatment and the impact of users on final consumption. Indeed, we still have a lot of work to achieve before to get to our ideal: 'Building Energetically Efficient and Ecologically'. We believe that to return back to 'nature' in ways similar to our ancestors, drawing from nature to meet our needs, could help us get closer to this ideal. Several attempts try to learn from nature that show us it is now possible to optimize the structure of the building, mechanical system and materials used to improve their energy performance ecologically. The following section will present the biomimicry and his contributions in the field that concerns us today.

3. Biomimicry (Biomimetic Design Strategy) Could Provide Guidelines for Improving Energy Efficiency of Buildings

3.1. Overview Biomimicry—Optimization Strategy from Nature

The main force related to the way nature can inspire sustainable design. The term 'inspire' means enabling the designer to look for creative design solutions [23]. One source of inspiration comes from the shapes of organisms. The second level of inspiration relates to the manufacturing process that operates in those organisms. At the last level, inspired by the interactions of the species between each other and by the global functioning of natural eco-systems [24]. A conceptual model of biomimicry has further classified the design approaches, which range for a 'direct' approach that is a simple mimicking process to an 'indirect' which involves more diverse forms of analysis of nature [25]. The question for research is largely a 'how' question to use biomimicry in design. One of the major challenges of using biomimetic strategy today is to provide sustainable technologies. To imitate nature solution per se, without an intention to implement nature sustainability design principles, is not a guarantee for sustainability. Seeking nature's guidance for sustainable models and measures is reasonable and has expanded in recent years. Biological processes operate within restricted living constraints without creating waste; in contrast they enrich and sustain the ecosystems. Nature forms and structures provide a wide range of properties with the minimal use of material or energy and nature systems demonstrate efficient flow of energy and material. Not only nature solutions are distant from technology, but they are also based on a different paradigm [26]. The different is well demonstrated the comparison between design solutions in biology and technology, by the assistance of the TRIZ [27], an acronym in Russian known in English as 'Theory of inventive problem-solving'. TRIZ based analysis showed that there is only 12% similarity between the principles of solutions in biology and technology. While in technology usually energy and materials are being used to solve problems, in biology solutions are based on information and structures [26], (Figure 2). Further more, biology system usually follows the principle of multifunctional design. Each component has several functions, offering an elegant and cost effective design. Technological systems not always follow this principle; in many cases each component has one or only few functions.

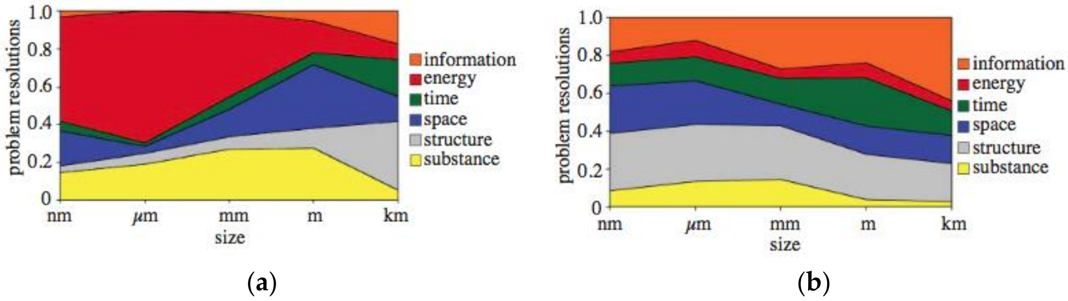
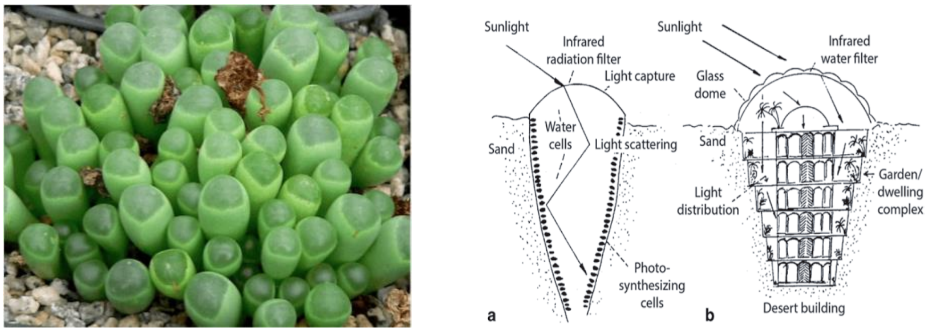


Figure 2. (**a**) The types of problem-solving strategies that human technology employs on different length scales [26]. Technology tends to function by manipulating energy and substance; (**b**) Types of effects observed in biology at different length scales [26]. Natural systems tend to function on account of how they are structured and the way information is managed.

To explore biomimetic strategies, which challenge this position, we use technology to aid designs, which are inspired and work with nature rather than being controlled by technology. Biomimicry has much to contribute especially during the concept generation stage with well understanding of performance optimization in nature. An appropriate sustainability tool for the concept design stage maybe derived from the nature itself, where nature sustainability design principles are identified and gathered as a tool such as database. We will speak further in Section 5, the research aim/methodology section, as to how we can facilitate biomimicry as a sustainable tool to manage energy consumption in the buildings.

3.2. Biomimetic Problem-Solving Design Strategies: Comparison between Nature and Architecture

If we look at all design solutions based from nature and compare with problem-solving contradiction in architectural design, one can find many commonalities between the two domains. For examples, the main purposes for windows are to allow light in and to let you see out and this often comes at the expense of their ability to prevent heat transfer. The contradiction is what if the building requires more light inside and at the same time the building must be able to control heat gain, how can we solve this contradiction within the same design concept? Once we look at the perfect solution in nature, in general we recognize that plants have many techniques for light harvesting, but what about one that can also control heat gain. One such example is Fenestraria aurantiaca (also known as window plant) [28]. Window plants have a similar working principle to fiber optics, it can be found in the deserts of South Africa, they are nearly buried in the sand [29]. The tip of every leaf is transparent: Light enters here and can travel down the leaf [29]. The plant shown in Figure 3a has only a small part of it exposed to the light. The plant absorbs light through an opening at the top, hence the name 'window plant'. Fenestraria aurantiaca has specialized adaptations to deal with heat, light and aridity. The window at the top of the plant is actually a light transparent membrane, light can protrude through this membrane to reach the lower region of the leave. The mechanisms from Fenestraria aurantiaca not only inspire cooling and light collections, but could also provide a feasible solution for architecture design. The concept of the window plant can be adapted for building in deserts and very hot regions (Figure 3b). The light collection combined with cooling effect could open new doors to building design. The concept of light collectors has been in existence for a long time and is constantly optimized. The fact that architectural design itself could provide light collection and cooling, without the need of additional systems, could result in sustainable building design.



(**a**) (**b**)

Figure 3. (**a**) Fenestraria aurantiaca [28]; (**b**) a. Abstracted from the build-concept of the stone plant Frithia pulchra (Adapted from Tributsch 1995): b. Concept sketch for a desert building [28].

By using a biomimetic design strategy, as an architect, to be able to automatically know which specific plant to look at, to understand the mechanism behind nature's perfect design and to choose what to transfer, are not easy tasks. Either an architect who has long–years experiences working in the biomimetic field or one that have an access to collaborate with biologists, botanists and share problem-solution design commonality between the two domains. The major concern of discouragement for architects to go for biomimetic strategy is because of the lack of biological knowledge and the lack of accessibility to reach to the correct biological information.

3.3. Biomimicry and Energy Efficient Building Design

For the design concept of an energy-efficient building, building envelope is the first to count on the consumption change, which will allow us to reduce energy needs by careful design of the building envelope. Recently, integrate biomimetic design in building envelope is one of the most development tool for energy management in the building. Nowadays, building envelopes are associated with a wide range of innovative technologies that significantly influence, in particular cases, have a functional role in providing a satisfactory indoor climate for the occupants [30].

Technology might be one of the main driving forces to transfer natures' principles to architectural designs. Architecture with aspects of nature has been there longs years from the traditional architectures until the modern ones. However, Biomimetic architectures have been developed just recently, started from the original concept of Biology + technology [31] intentionally creates more efficient artificial design. Nowadays, with global problems, biomimetic design is developing to integrate towards more sustainable concept. To reduce enery consumption in buildings is not all about re-construction the whole building itself with the most innovative and advanced technological design possible, as biomimetic architecture frequently is misinterpretated. This is where the initial thought of the optimisation's principle from nature should be aware of. If we want to imitate an efficient design from nature, we must not forget to also learn to imitate the process of how nature achieves it. This process is the lesson to reveal all the secret of high-performance design optimisation from nature that can make us differ from an architectural perspective. There is an important distinction to be made between 'biomimicry' and 'biomorphism' as the architects frequently use nature as a source for unconventional forms and for symbolic association. Nature is the ultimate in performance-orientated design so it is no wonder that attention should finally be paid to its processes. Rather than just symbolic or form, biomimetic architecture should be concerned more on aspects of how we process our design and what if our design could be a positive impact to the environment as a whole [32].

Although nature is the perfect design model for us to learn and develop in our man-made design, to mimic the process of nature is not a trivial task. There are various obstacles to the employment of biomimicry methodology in design. One barrier of particular note is the lack of a clearly defined approach to biomimicry, especially if the goal is to increase the sustainability and energy consumption.

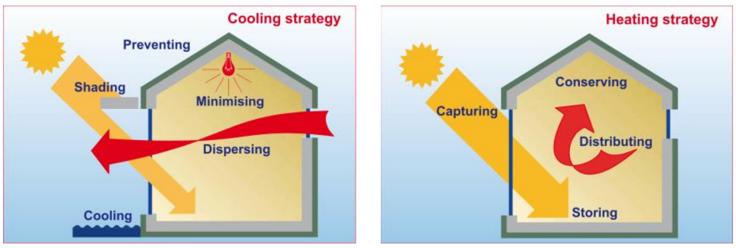
Drawing on the principles of biomimicry in energy-efficient building design offers such a path. In order to understand both the urgency and the benefits of using a biomimetic approach to energy-efficient building design, it is first necessary to explore the energy efficiency or effectiveness of biological organism and systems at consuming energy. The incentive is that by creating more energy efficient system and technologies, and begin more efficient at energy consumption ourselves, we would require less power, and in turn less fossil fuel is burnt and therefore less GHGs are emitted into the atmosphere [33]. The objective is to employ biomimicry in the further improvements and developments on existing means of producing, generating or capturing energy to reduce human dependence on fossil fuel that still dominate our energy consumption. Various biomimetic technologies and products have been developed for the purposes of improving energy efficiency. There are numerous examples of living organisms and systems that are highly energy effective and that could yield an understanding of how humans could build and carry out their activities without a dependence on fossil fuels [34].

4. The Analytical Study of Bioclimatic and Biomimetic Design Strategies to Reduce Energy Consumption in the Building

As we have referred to in the first chapter, humans have always taken advantage of local conditions to construct their shelter to suit their needs and architecture with aspects of nature. This has been true over the longs years from the traditional architectures until the modern ones. The evolving sustainability approach to building aims to use energy and resource efficiently, and to use environmentally friendly outputs. It can be achieved by looking at the relationship between architecture and nature from the past until present (e.g., vernacular architecture, bioclimatic architecture). Using successful traditional design principles that respond to human needs and environmental conditions combined with advance modern science and technologies where natural strategies can be applied directly to the design construction and its process (biomimicry). This approach may lead to functional design solutions that interact with the environment, where technology becomes an integral part of the environment as well [35]. This includes evaluating the main similarities and the driving forces that affect nature and the architectural design process [36]. We introduce an analytic study for two examples: one shows bioclimatic design in comparison with biomimetic design in objective to reduce energy consumption focusing on technique and strategies applied.

4.1. Bioclimatic Architecture Approach: The Cooling and Heating Design-Strategy

Bioclimatic architecture is defined as an architecture, which has a connection with nature; it is about a building that takes into account the climate and environmental conditions to favor thermal comfort inside [37]. This architecture seeks perfect cohesion between design and natural elements (such as the sun, wind, rain and vegetation), leading us to an optimization of resources. Bioclimatic designs take into account climate and environmental conditions to help achieve optimal thermal comfort inside. It deals with design and architectural elements, avoiding complete dependence on mechanical systems, which are regarded as support. A good example of this is using natural ventilation or mixed mode ventilation (Figure 4).



(a) (b)

Figure 4. (**a**) The cooling strategy, reduce calorie intake and promote refreshment; (**b**) The heating strategy promotes free heat gains and reduces thermal experts, while allowing sufficient air renewal [37].

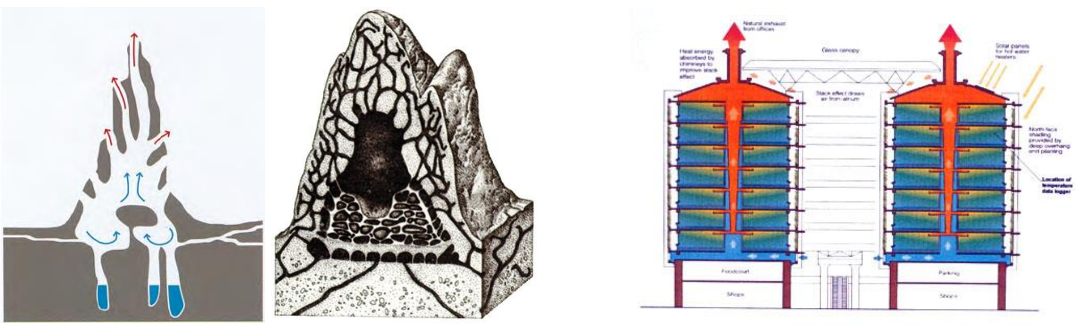
The purpose of Bioclimatic design is to reduce the energy consumption rate required to operate a building while enhancing the quality and comfort of the indoor environment for occupants. For example, to provide comfort during the summer requires a cooling strategy: protection from direct solar gain and glare, minimizing heat gain, dissipating solar heat gain and cooling naturally. Comfort in the winter requires a heating strategy: Utilizing solar gain, storing it in thermal mass, retaining heat through insulation and transmitting it throughout the building.

Designing with nature means accounting for multi-seasonal considerations, for example, reducing heating needs with maximum sunlight from Southern oriented windows. If these techniques have worked for generations in these communities designed for their geographic region, then clearly modern design could benefit from careful integration of these traditional principles. It is entirely possible to design modern bioclimatic housing and architecture, using natural ventilation, passive solar design, sustainable materials, and many other traditional site-specific techniques. Bioclimatic architecture deals exclusively with traditional building design accounting to climate and environmental conditions, but it works at different scales to the concept of biomimicry, in which nature is the mentor for the concept of the design and its process as shown with the analysis study of the termite mound and the penguin feather.

4.1.1. The Architecture of Termite Mound: Auto Cooling-Heating System with Ventilation and Air Exchange Management

The remarkable architecture of termite mound teaches us many lessons how to construct a high performance building, it keeps the temperature almost constant at all time. What ever the climate outside would be, inside the mound is always stably 87 F° [38]. Termite mound is an efficiency ventilation device. If the termites were the same size as us, their mound would have been the size of Empire state building. They teach architects to design super-efficient skyscrapers. Inside the mound is an extensive system of tunnels and conduits that serves as a ventilation system for the underground nest. In order to get good ventilation, the termites will construct several shafts leading down to the cellar located beneath the nest. The mound is built above the subterranean nest. The nest itself is a spheroidal structure consisting of numerous gallery chambers. The termites create channels inside through the wall that it can breath. We learn from the termites to improve our design that the walls should work as membranes to breath rather than barriers [38].

The Eastgate Centre, Harare, Mick Pearce has optimized the ventilation of the building, the architect found inspiration in termites' mounds (Figure 5). Their structure responds to external air movements and humidity in order to keep the interior cool. Although the result shows 90% reduction of energy required for air-conditioning compared to building of the same size. Remarkably, these designs are still based upon an erroneous conception of how termite mounds actually work. If we could arise from this better understanding in the structure and function of termite mounds, we could create a new outline for biomimetic design concept in the future.

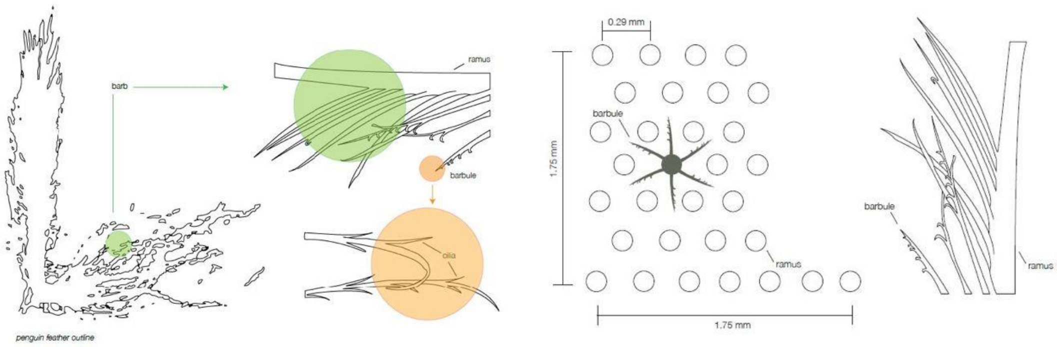


(**a**) (**b**)

Figure 5. (**a**) The architecture of termite mound [38]; (**b**) The Eastgate Centre, Harare [39].

4.2. Passive Mechanism for Thermal Comfort: Double Wall and Biomimetic Insulation (Penguin Feather)

Appropriate design of building insulation can facilitate heat retention during winters and prevent ingress of heat during summers. One of the finest examples of insulators for heat retention is the feather of the Gentoo Penguins (Pygoscelis papua) from Antarctica [40] (Figure 6). According to the anatomy of the penguins, maximum insulation is achieved due to the closely packed arrangement of the feather on the body of the penguin, it minimize very well the heat lost. Thus, creating a thermal model based on the penguin's feather follows this main principle. The biomimetic material based on the arrangement of the penguin feather is tested on the main façade instead of the double wall in building simulation [41]. The comparison of results between building with double wall façade and with biomimetic façade material shows that through the biomimetic material, very minimum heat loss occurs from the building fabric in winter but in summer the building is more airtight. In terms of comfort during winters, the biomimetic façade material is able to produce more comfortable conditions than the double wall system. This is because of the insulation quality of the façade material that retains the heat in the interiors. Comparing energy-efficiency with the energy required for heating, biomimetic façade material requires only half of the heating consumption compared to the double wall façade. Whereas during summers, the double wall system is able to deliver more comfortable conditions than the building with biomimetic façade material. This is because the double wall can delay the ingress of the heat in the interiors due to air gap in the façade. Hence, the biomimetic façade material is more efficient during winter period [41]. This analysis will be used as an example of penguin feather as biomimetic strategy to test multi-criteria requirements and result with the investigating tool in Section 5.



(**a**) (**b**)

Figure 6. (**a**) Feather structure of penguin [41]; (**b**) Feather distribution on penguin [41].

Comparison of results show that the building with biomimetic façade cladding material, inspired by the structure of the penguin feather, is better comfort during winter. The biomimetic façade produce more efficient winter heating than summer cooling. Biomimetic design is not always the best solution for the thermal comfort unless we are aware of specific criterion. In the case of biomimetic façade, it is certain that appropriate emulation from nature has enables construction of effective materials that can address the energy issues of a building, but it is specifically recommended only for heavy construction in extreme cold weather because of its superior insulation quality and fabric performance.

Biomimetic design could be a favorite in the right place where nature is the mentor for the concept of the design, using efficient overall structural forms, functions and how to manufacture materials to employ the design to maximum effect [42]. After the analytic study, although nature is a potential source of inspiration for creating energy-efficient structure but it depends on multi-criteria requirements such as climate classification, environmental factors, material used, type of construction and etc. The value and relevance of using nature as a model in the context of the design of energy-efficient buildings is proven, difficulty, and size, nevertheless persists, to the architects, who do not familiar with biological process, unless in a research perspective or prospecting. This state of affairs is due to ignorance and/or the fact that much of the architects relegate biomimicry to a level of research "utopian" perspective view. The question at this point of our work is that to say, how can we do to that architects go a little more "spontaneously" and/or more "naturally" to this type of approach? This would facilitate the one hand, their initiation Biomimetics demonstrating and making available its interest by examples from the architecture (and in terms of what they know) and, secondly, the inspiration or exploitation of biomimicry in their work. To achieve this goal, we suggest to formalizer the biological and architecture knowledge, within a virtual platform (computing) collaborating between biologists and architects, where biologists feed biological information into the database and facilitate by investigative tools to bridge with architectural design concept. In this article, a decision support tool based on Bayesian networks is hypothetically chosen for testing the rapid result, between the choice of natural devices impact on various criterions in specific case study, which we describe the operating mode in the following section.

5. A Platform and Investigative Tool for Integrating Biomimetic Strategies in Serving Energy-Efficient Building Design

The goal of this study is to create a tool to search for and bridge the relationship between natural devices and architecture. We propose to create a platform to formalize the knowledge between biology and architecture along with investigating tools that assist architects what biomimetic strategies to choose and to explore further according to multi-criteria requirements (e.g., type of operation, structure, scale, climate classification, time, comfort summer or winter, etc.). Furthermore, the platform of the tool will help to save time during initial stage of exchanging knowledge between biologists and architects, as the tool can help to find the link between the two domains according to their common design concepts and phenomena interacting with their environmental conditions [43]. While the role of biologists is to feed the database on biological knowledge and the role of architects is to feed the architectural design knowledge in parallel (Figure 7). After formalizing the relationship of the two domains, multi-criteria choice assistance and decision-making tool could be introduced according to specificity in each project. In this article, we have hypothetically suggested the Bayesian network as a testing result in serving energy-efficient building design.

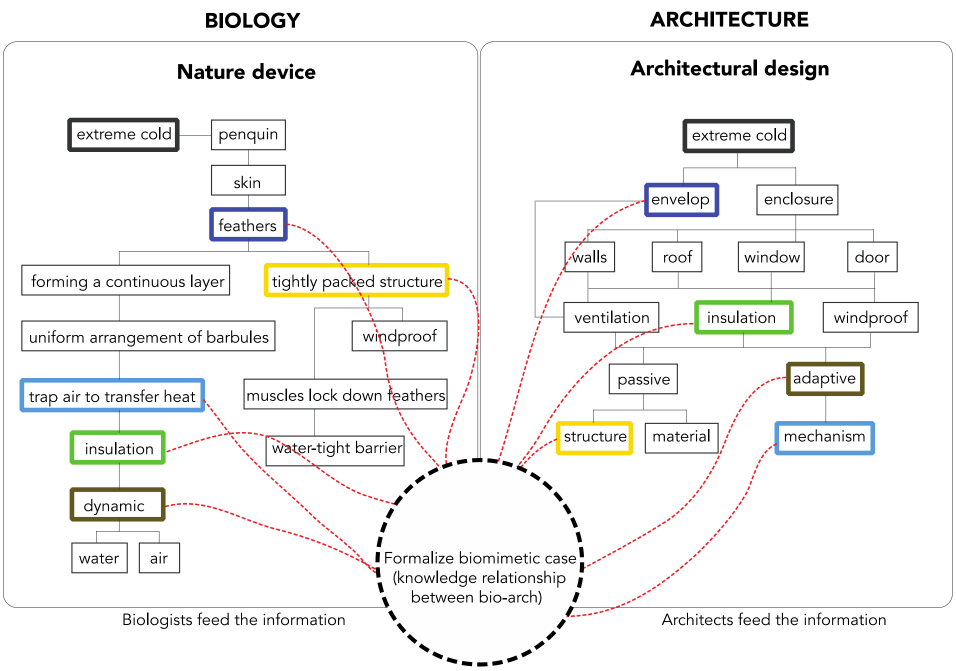


Figure 7. An example of a small network within a data analysis platform (computing) searches and formalizes the relationship knowledge between biology and architecture.

5.1. Presentation of the Tool

This tool is designed to guide architects and engineers, or other building actors. It is both an information investigating tool and an aid in selecting the most appropriate strategies of nature to the needs and specificity of a project, all this in connection with energy performance and optimizing suit specific needs, special features and characteristics of each project. This tool will enable building professionals to learn about biomimicry, what are the known strategies and an applicable implementation of the building from an energy point of view. Secondly, it would allow them, during the design process, from the data they have of their project to define strategies from nature and could be a potential inspiration to optimize their design in order to reach their goal of energy efficiency, optimal way in terms of cost in materials, embodied energy, etc. (all evaluation criteria will be specified during the design of the tool). The proposals made by this tool could be applied to different levels of the project, namely: (1) the development of an innovative material; (2) specification of project components such as a front portion and; (3) part of a broader strategy that would be part of the envelope, for example.

To do this, we propose a tool in which structure would be as follows (see Figure 8): initially the architect, for example, should integrate through an interface, project-related input data and natural devices that wish to be treated. These inputs allow feeding a multi-criteria assessment tool that we produce output options that can offer one or more kind of strategies form nature and constraints to their adoption. For each biomimetic design strategy, a data sheet describing the natural role model's information, examples or operating potential in the building that would be accessible in a database, fueled by the question of experts. This database will integrate the different strategies that can be associated with an element of nature. Each one contains information on the natural phenomena, a system diagram drawing (our architectural drafting-drawing to abstract natures' principles), references, contacts of scientific experts and case studies (where the strategies have already been applied).

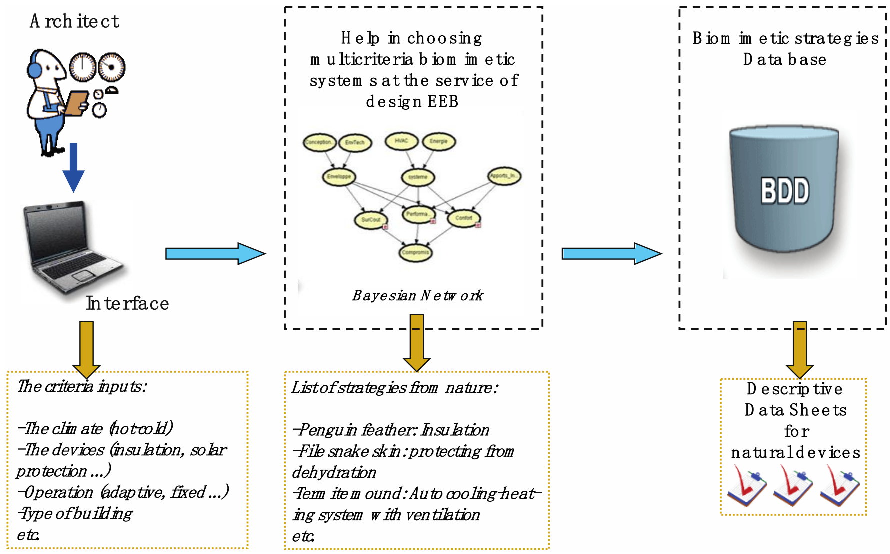


Figure 8. Presentation of the structure of investigating tool, which can support architects to use biomimetic strategies in more applicable way.

In order to achieve this, we will use the biomimetic case from the platform that formalize already the relationship between nature device and architectural design/elements then we must;

1. Identify inputs:

    a. Identify the needs of architects in terms of optimization and development of solutions (passive system, adaptation system, structure, material, etc.)

   b. Identify the factors that interact with this system (climate classification, type of operation, constraint, objectives, etc.)

2. Identify outputs: Identify strategies from nature that could be useful in the design of energy-efficient building. After we design the tool and construct the network, we offer an open system where scientists and architects could incorporate useful knowledge and working together on biomimetic project.
3. Implement the tool: This tool should help connect the needs of the architect in terms of innovative design related to nature's strategies (in this article is to reduce energy consumption in buildings) taking into account the project context (environment, type of project, its morphology, its occupants, etc.) the project could take the following form (Figure 8). The implementation of the multi-criteria assessment tool will be hypothetically based on Bayesian networks, which can rapidly present the results in the following section.

5.2. Bayesian Network (BN), Investigating and Decision-Making Aid Tool

For the hypothesis of the investigative tool we propose Bayesian Networks (BN), as it seems to us adapted the complexity in which we are confronted. Bayesian network is based on Bayes' theorem, which is based on the conditional probability. The Bayesian networks are generally used to represent a cause to effects reasoning [44]. They are adapted to decision-making aid tools, and used for different applications: risk management, finance, medical domain, etc. As presented in the Figure 9, a Bayesian network is a graphical model in which knowledge is represented as variables. Each variable is represented by a node in the graph (as a qualitative representation) and has different attribute (or stat). The relationship between causes and effects are translated by directed arrows that link these nodes. The quantification of the effect that can have the causes is represented in a conditional probability table (Figure 9).

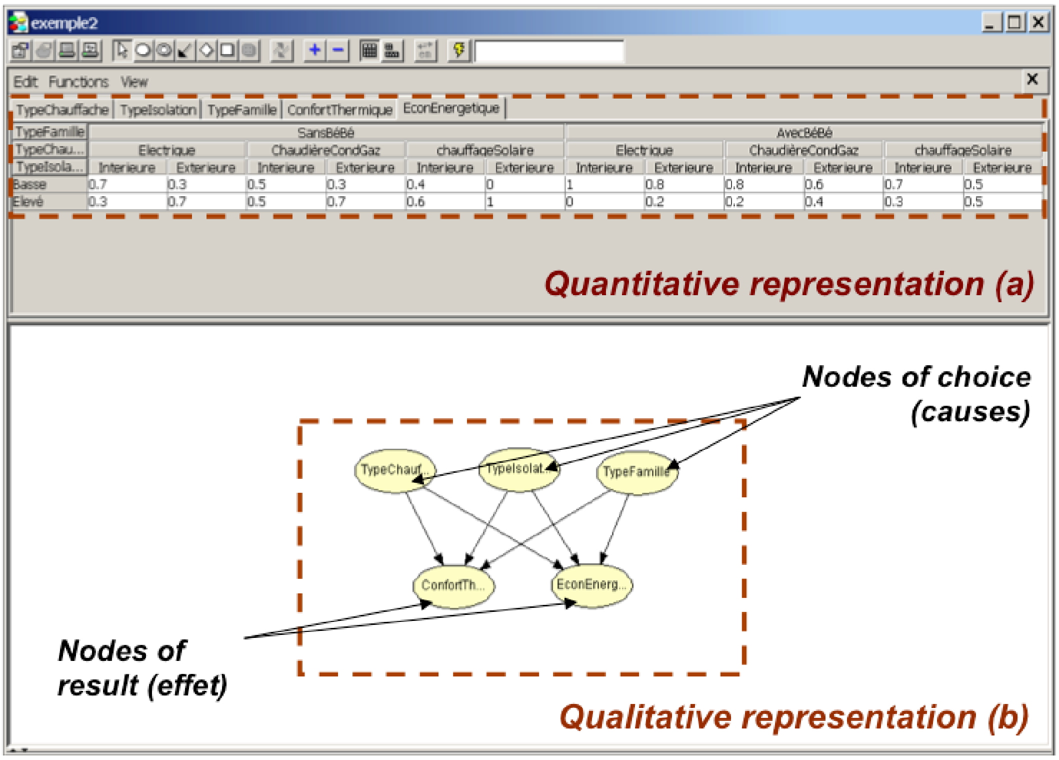


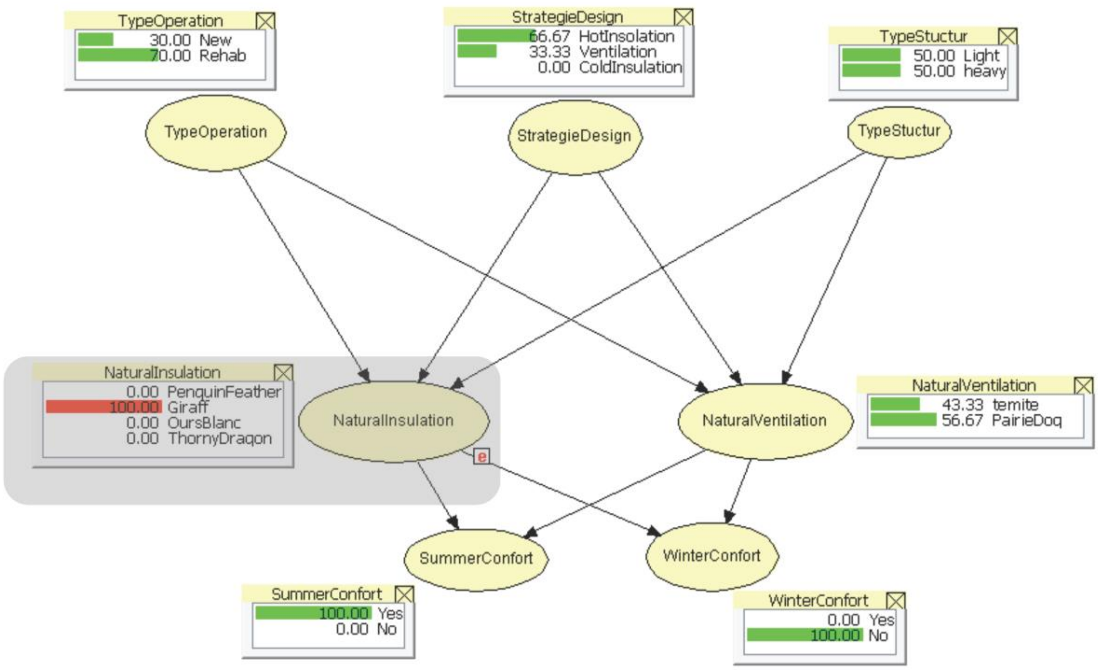
Figure 9. Implementation of a Bayesian network; (**a**) Filled Informations conditional probability tables; (**b**) Graphic description model. Bayesian network interface HUGIN [45].

The first interest of proposing the Bayesian network is that it could be used in domains where knowledge is not explicit and difficult to control. A Bayesian network permits identification of the relationships between pieces of information about the project that could appear independently [46] as the relation between type of users and energy performance [47] (Figure 9). The second interest of the BN is that it can be used in the two directions: from effects to cause (information given, Figure 10) and from causes to effects (decision-making aid, Figure 11). Thus, it is possible to evaluate the effects of causes or to find out the possible causes of a given effect. To be shown in Figures 10 and 11.

We propose presenting how the tool will run through this small network (Figures 10 and 11). The network presented in these figures consists of 7 nodes (or variables). It will help to identify ventilation and insulation strategies from nature (2 nodes), which respond to particular indications or constraints. These responses will be based on three nodes of inputted information: the type of operation, the design strategy and the type of structure. It will also provide guidance or against-indications related to comfort, summer and winter (two nodes). These nodes are connected, cause and effect, through directed arrows. Indeed, if we take the case of identifying an insulation strategy for example, we know that the choice of type of insulation inspired by nature depending on the type of operation (renovation or new construction) and robustness of the structure. We also know that this choice can be adapted or not to the summer/winter comfort, depending on the case. Each node representing a variable that can have multiple attributes (or states): variable comfort summer, for example, has two states: positive (Yes) or negative (No), the probability of being checked is varied from 0% to 100%. This network can be used from top to bottom, or from bottom to top as follows:

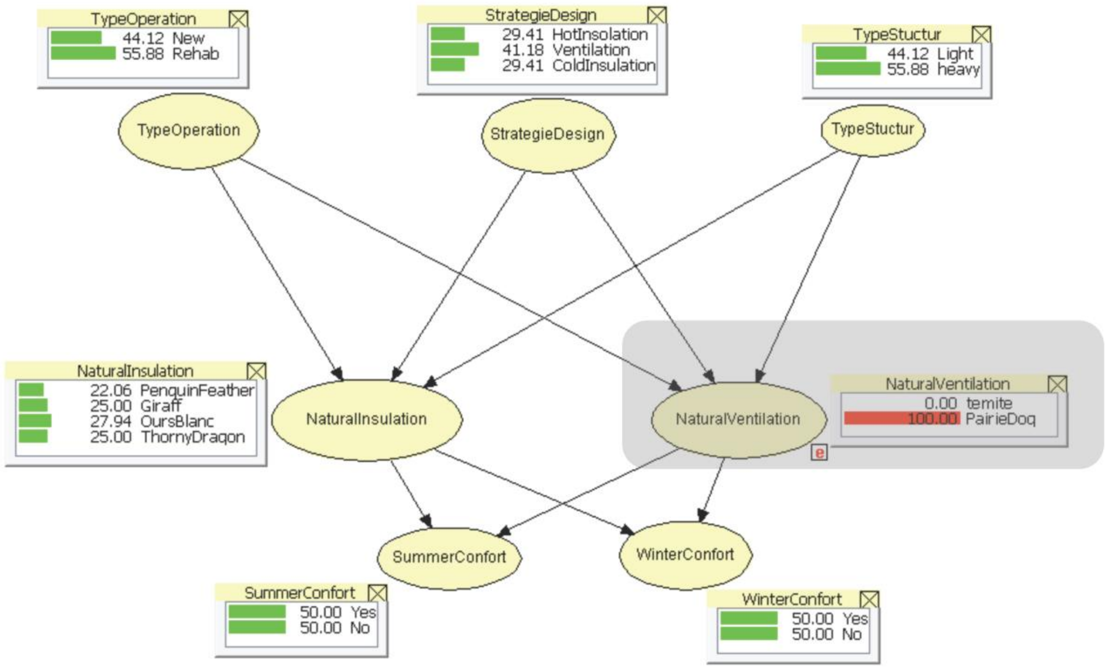
5.2.1. Information Given Tool: Exploring Nature Strategy to Suitable Multi-Criteria Requirements

The spread upwards (exploring nature strategy to multi-criteria requirements) will allow users of the tool to extract, from the Bayesian network, information on areas of relevance (climate classification, design strategy, type of architectural construction and etc.) to use nature strategy and possibly to learn about the constraints of these strategies, or problems they can create for other positions. Such as the BN will inform us about the fact that this strategy is effective for winter comfort and can cause problems in the summer comfort.



(a)

Figure 10. *Cont.*



(**b**)

Figure 10. Information given tool: exploring nature strategy to suitable multi-criteria requirements (**a**) Potential use of Giraffe skin as natural insulation strategy; (**b**) Potential use of Prairie dog as natural ventilation.

As shown in Figure 10;

(a) Choosing giraffe as insulation strategy from nature (100%), the information shows that it is better to develop this strategy with an already existing building (70%), integrates with heat insulation design-system to release the heat out (66.67%) and regard to type of structure, it works both with light or heavy structural building (as show equally 50%). The BN also informed us about the fact that this strategy is highly effective for summer comfort (Yes: 100%) but not for winter comfort (No: 100%).

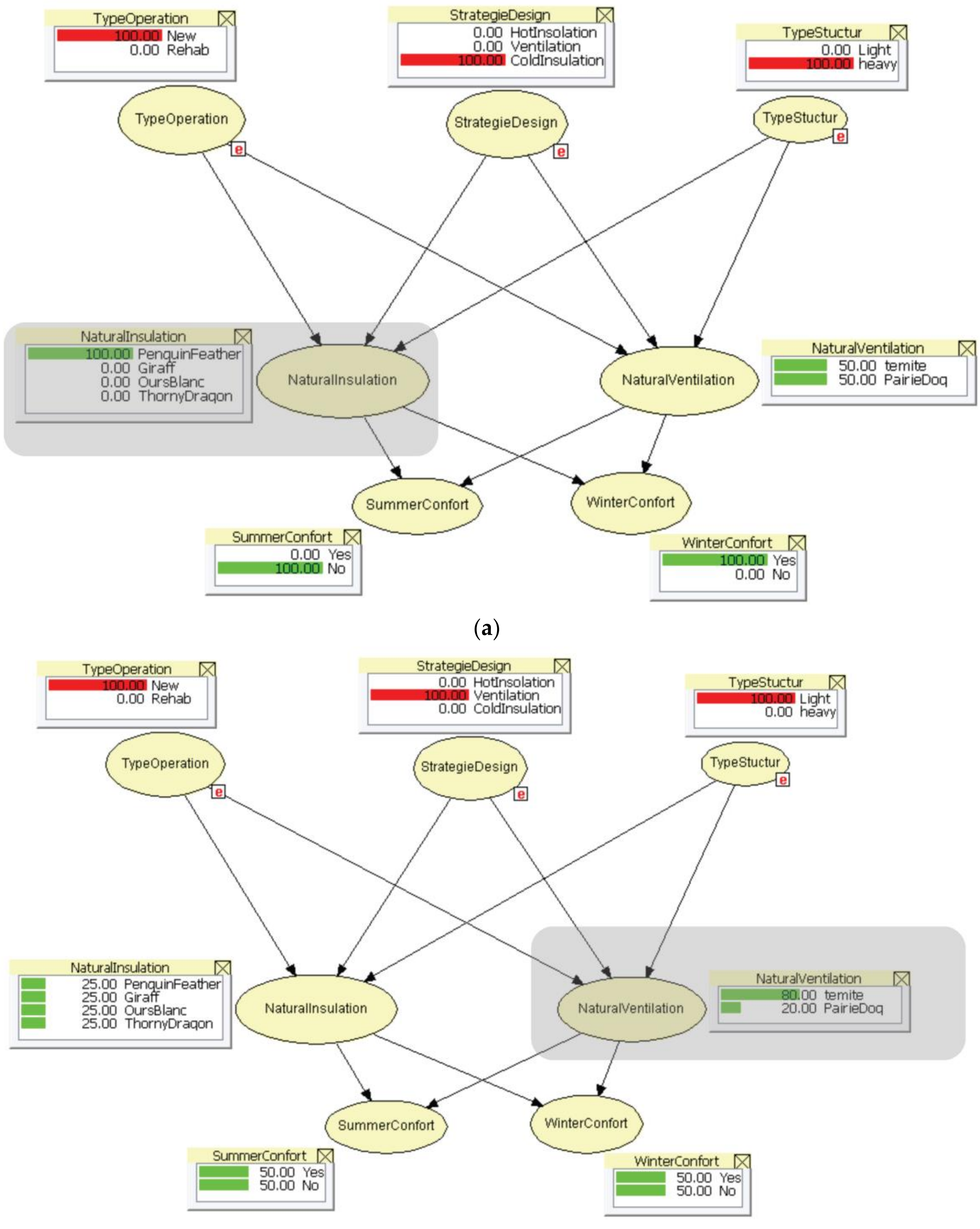
(b) Choosing Prairie dog as ventilation strategy from nature, the information shows that it is better to develop the strategy with an already existing building (55.8%), integrates with ventilation design-system (41.18%) and it works better with heavy structural building (55.8%). The final alert shows that this strategy works both for summer and winter comfort (as show equally 50%).

5.2.2. Decision-Making Aid Tool: Selecting Nature Strategy According to Multi-Criteria Requirements

The spread up down (multi-criteria requirements select biomimetic strategy that is most suitable to elaborate further) allows users to identify a strategy from nature, which best suits to meet a particular needs and to avoid difficulties or incompatibilities that these strategies can have with other concerns, comfort, for example (all in 100%). We can identify the input selection proposed attributes, which are both design and other information strategies such as structural constraints or type of operation.

In the case presented in Figure 11 below, the inputs are the following:

1. Type of operation is “new construction/renovation”
2. Design strategy is “summer or winter insulation/ventilation”
3. Type of structure is “heavy/light”.



(a)

(b)

Figure 11. Decision-making aid tool: selecting nature strategy according to multi-criteria requirements (**a**) What nature strategy is the most appropriate for winter insulation with new construction and a heavy structure? (Penguin Feather 100%); (**b**) What nature strategy is the most relevant for natural ventilation in new construction and a lightweight structure? (Termite mound 80%).

As shown in Figure 11:

(a) We specific the requirements of the project (multi-criteria) that we need a strategy from nature, which is for winter insulation design, with new building type of operation and with heavy structure (all in 100%). The BN tool suggests that the best insulation strategy from nature to explore in this project context is from the Penguin Feather (100%). The final alert, it is precisely recommended to use this strategy for winter comfort (Yes: 100%) and it might pose problem for summer comfort (No: 100%).

(b) We specific the requirements of the project (multi-criteria) that we need a strategy from nature, which is for ventilation design-system, with new building type of operation and with light structure (all in 100%). The BN tool suggests that the best ventilation strategy from nature to explore in this project context is from the Termite mound (80%). The final alert shows that this strategy works both for summer and winter comfort (as show equally 50%)

Another interest of BN is the possibility of learning process that can be done on two levels: to perfect the graphic model (relationship of variables (criterions)), and to supply the tables of probability with the most relevant resulting. Indeed, this possibility would allow us to refine our tool incorporating with the multidiscipline expertise of scientists, biologists and architects to upgrade the information and to complete the model by identifying relationships between natures' principles and multi-criteria of the architectural design project. Furthermore, the BN can help to save time along with cognitive learning process to search for new strategy from nature by the AI algorithms used (learning and inference). This uncertainty can be due to imperfect understanding of the domain, incomplete knowledge of the state of the domain at the time where given a task is to be performed. To construct network of the tool is a genuine multidisciplinary work. Therefore, it allows experts from different fields to work together during the process of feeding the probability tables (based on knowledge and facts) and building graphic model relationships between variables (criterions).

6. Future Development for the Project

We intend to continue further these research studies in a multidisciplinary project. To construct this investigating tool at the initial stage, it is necessary to associate between cross-organization experts from biologists, architects, builders, data processors, etc., to feed and exchange knowledge and facts based on related disciplines. After we construct the tool, we will test with numbers of project implementation on energy-efficient design, we will measure with the time-saving, learning process and effective of choice assistance of nature's strategy, according to multi-criteria requirements. The initial stage is to formalize the relationship knowledge between nature devices and architectural design concepts. Thus, we can create a biomimetic case within the database for further investigation according to multi-criteria and specificity of each project implementation. For creating the BBD (biomimetic case database), we will cooperate with CEEBIOS (Centre Européen d'Excellence en Biomimétisme de Senlis) [48], as they have access to biological information according to biomimetic design needs. We will combine their biological information with our architectural design concept, drawing the problem-solving design of each nature's principal to fit in to architectural design implementation.

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