Bio-inspired Kinetic Envelopes: 
Integrating BIM into Biomimicry for Sustainable Design

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Abstract

In the architectural field, air-conditioning systems are designed to maintain thermal comfort even if the surrounding temperature changes. At the counterpoint of the biological field, thermoregulation enables an organism to keep its body temperature within certain boundaries through morphological changes according to variations in the surrounding temperature. This research explores the potential for using analogies drawn from a natural model to create Bio-inspired Kinetic Envelopes (BKE) for utilizing solar radiation and responding to changing temperature, thus minimizing the energy needs of air-conditioning systems. Ideally, the energy needs of air-conditioning systems can be reduced through the BKE behaviors based on bio-inspiration.

The project integrates a new approach by using Parametric Design in BIM (PDBIM) to establish parametric relations between envelope physical models and climatic conditions to translate the biological thermoregulation behavior into the possible architectural configurations and kinetic modes. The translation process will include analysis of the selected climate, reports of the possible shaping and composing of envelopes, analytical tests of energy usages of the resulting building envelope system in terms of thermal comfort.

Funding for this design research aims at creating specific bio-inspired building envelopes for climatic temperature responsiveness and increasing the efficiency of the building thermal environment based on BIM parametric design. The expected long-term achievement is a new design approach integrating BIM parametric design and biomimicry for energy efficiency and interactive building expression.

Keywords: bio-inspired design, sustainable design, BIM parametric methods
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1.0 Background

Thermophysical and optical properties of building envelopes play an important role for the building’s energy consumption and indoor environmental conditions. In recent years, some promising and innovative building envelopes have tended to be more adaptive and interactive with environments, occupants (or visitors), and specific components. These kinetic envelopes’ technologies range from a simple automated blind for a better use of daylighting, to smart glazing, variable wall insulation, sliding walls, moveable roofs, and other active parts. Compared with the static or fixed properties of traditional building envelopes, these kinetic features are designed to actively respond to prevailing climatic conditions including solar radiation, daylight, wind and other factors, and for enhancing indoor environmental comfort levels.

In the field of nature, biological acclimatization (e.g. thermoregulation) enables an organism to keep its body conditions within certain boundaries through morphological, behavioral, physical and/or biochemical changes according to variations in the surrounding climatic conditions (“Acclimatization” n.d.). Acclimatization occurs in a short period of time (days to weeks) within the organism's lifetime, such as seasonal changes of mammals’ fur and behaviors of plants’ leaves or flowers. Also, many studies in the biomimetic area have already shown that natural models can achieve highly efficient results (Bar-Cohen, 2005).

We hypothesize from the previous discussions that the biological acclimatization may be transcribed into kinetic building envelopes. This research explores the potential for using analogies drawn from natural models to create Bio-inspired Kinetic Envelopes (BKE) for utilizing natural resources and responding to changing environment thus minimizing the energy needs. Ideally, the energy needs of air-conditioning systems can be reduced through BKE motions based on bio-inspiration.

2.0 Objectives

The expected long-term achievement of the research is an innovative bio-inspired design solution for kinetic building envelopes for energy efficiency, and in turn it connects biomimicry to sustainability. Regarding this grant project, the objective of the study is to create a particular bio-inspired kinetic building envelope for climatic temperature responsiveness and enhancing
building energy efficiency. The mechanism of the kinetic composing and shaping is based on a natural model about butterfly wings’ honeycombed structure. The project integrated a new approach by using Parametric Design in BIM (PDBIM) to establish parametric relations between envelope physical models and climatic conditions and to translate biological thermoregulation behavior into the possible architectural configurations and kinetic modes.

In particular, the research is needed to resolve the following questions:
1) What kinds of climates are required to consider the kinetic features?
2) What attributes of the biological model may be used for building thermal issues?
3) How can we model, simulate and comprehensively identify the design of kinetic building envelopes inspired by biological acclimatization?

3.0 Methods

To resolve the aforementioned questions and investigate energy merits of BKE, we adopted the following methodology about an experimental design of a non-traditional building envelope in a selected climate.

3.1 Analyses of weather data

Analyzing the weather data of a selected city is expected to contain sufficiently potentials to apply BKE features and display the design process of BKE. The city Beijing, China (Longitude 116.5° E, latitude 39.8° N) was selected as the design site, and it has obvious seasonal differences. Non-residential buildings’ heating and cooling loads occupy almost a half of the whole energy consumption (Beijing Municipal Commission of Urban Planning [BMCUP], 2005). Also, according to the latest version of “Design Standard for Energy Efficiency of Public Buildings Design Standard for Energy Efficiency of Public Buildings,” Beijing is categorized into the Cold Climate Zone in China and U-value of walls should be below 0.8W/K m² *(BMCUP, 2005).

We used the CSWD (China Standard Weather Data) (Jiang, 2005) downloaded from DOE’s website, and the Weather Tool to analyze the climatic variables including air temperature and solar radiation. Figure one shows the monthly average outside temperature between May and October is around the adaptive comfort band. The adaptive comfort band is created by the Weather Tool and was studied by Humphreys & Nicol (1998) who give equations for calculating

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*The value is K-value in China which is from a little different measurement method but same definition and functions compared with U-value in U.S.
indoor comfort temperature from monthly average outside temperature. Further, by importing the weather data into Excel, we got more detailed information about hourly mean temperature and found there is approximately 18.3% time with appropriate values. Therefore, lower and static U-value walls may retard positive heat transfer. On the contrary, some kinetic features like variable wall insulation can ideally respond to this conflict and utilize the natural resources.

![Figure 1 Annual Dry Bulb Temperature and Adaptive Comfort Band](image)

We also conducted an annual solar radiation analysis of Beijing for a vertical surface facing south as following figure 2. The highlighted yellow line displays average incident solar radiation. It shows a very clear conflicting condition where the coldest months with blue color have much more incident solar radiation than the values in the hottest months with red color. Although it is that, during the summer, the duration with solar is longer and the total incident amount is larger, we still should utilize the higher hourly and the average solar radiation in winter for energy efficiency. The solutions may be related to certain kinetic technologies of building skins which can harvest the incident solar radiation in winter by specific shaping and composing, and change back to regular surface postures in other seasons.
3.2 Selection and investigation of biological model

Based on literature reviews, the research adopted a natural model of Lepidopteran thermoregulation, which refers to the specific wing structures and the basking behaviors of Lepidopteron in this study (Heilman & Miaoulis, 2004). In particular, discoveries on butterfly wings show that the honeycombed microstructures on the wings’ surface can be effective solar collectors (Heilman & Miaoulis, 2004). The honeycombed pattern is able to effectively use the
trapped solar radiation because of its total internal reflection. In other words, after the solar radiation enters the concave combs, it is partially absorbed and partially reflected, and nearly all the incident radiation is transferred within the honeycomb rather than being moved outside (Zhang et al., 2009). Conversely, the folding wings minimize the area of the wing surface and avoid overmuch thermal transmission.

### 3.3 Modeling methods and process

1. **The parametric design of building information modeling (PDBIM)**

   In order to model and support kinetic envelopes, we proposed a parametric design method based on BIM. There have been many experiments with introducing the parametric design, defined usually as the exploring, representing or optimizing geometry and forms from the aesthetic perspective in the fields of art and architecture (Bruderlin & Roller, 1998; Lee & Kim, 1996). However, the parametric design method in this research refers to the integration of BIM. The 3D knowledge-rich parameters are the fundamental point for BIM conception related to several modeling platforms like Autodesk Revit, ArchiCAD, and etc. The building model established on these platforms will have multi-parameters including constructions, materials, costs and user defined parameters. Those parameters set up a possible bridge to allow building information to connect climate and building energy. In addition, BIM authoring software, such as Autodesk Revit Architecture suits, offers an Application Programming Interface (API) designed to allow users and external application developers to integrate their applications. This study used Autodesk Revit 2010 and its API component.

2. **The process of the modeling (Fig. 4)**

   We translated the natural honeycombed structure into BKE panels with hexagon structures. The panel has basic supported frames made of brickworks and kinetic absorption cores made of phase change thermal storage materials. According to this biomimetic objective, we set up a design model of BKE panels at the “family” level in Autodesk Revit. Also, the program allows users to have detailed settings on the materials of the models. Each hexagon structure of BKE has two principle parameters, which are the “Height” and the “U-value”. These two important parameters will be changed according to seasons, solar radiation, outside air temperature and inside human activities. Logically, BKE panels can be changed to three periodic patterns including concave, convex and flat (Fig. 5, Fig. 6); meanwhile, the absorption materials’ insulation changes according to the outside air temperature.
Figure 4 The Translating Process of Bio-inspiration from the Butterfly
a. The microstructure of wings; b. Parameters of each panel; c. The composing of envelopes; d. The shaping of envelopes; e. The resulting building model.

Figure 5 The BKE panel and its kinetic modes in Autodesk Revit
Through API of Autodesk Revit, we also set up a visual interface for the behaviors of buildings (Fig. 7). The interface allows users to type the values of outside temperature, solar radiation and choose levels of indoor activities, and then generates different scenarios of building envelope shaping and composing as shown in the following figures.

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**Figure 6. The functions of single panel**

- **Winter’s daytime**
  - Absorb the outdoor solar radiation
  - Minimize the envelope area and retard heat loss
- **Winter’s nighttime or cloudy**
  - Absorb the outdoor solar radiation
  - Minimize the envelope area and retard heat loss
- **Summer’s daytime**
  - Minimize the area and reflect sunlight
  - Absorb the indoor heat and facilitate heat loss
- **Summer’s nighttime or cloudy**
  - Absorb the indoor heat and facilitate heat loss

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**Scenario 1**
-summer nighttime or cloudy, rainy day
3.4 Energy Analysis

The parametric model created from Autodesk Revit has kinetic behaviors and dynamic material properties; therefore, energy simulation tools should have capabilities to understand the kinetic features of BKE. However, most energy simulation tools work for fixed values of building materials and cannot account for changing building geometry during a simulation process. Separated phases with different settings and geometries will not only take many tedious works but also fail in limitation changes. The best approach for parametric models of BIM is to use an embedded energy analysis tool in Autodesk Revit, but the existing tools (e.g. Project Vasari and gbXML) can’t understand kinetic features. Although EnergyPlus and DOE-2 can offer some variable material properties, these programs are still difficult to utilize for complex kinetic models. Therefore, effective simulation methods are still pending at this stage of the research.
4. Conclusions

4.1 Potentials and limitations of BKE

Compared with the static or fixed properties of traditional building envelopes, kinetic features are designed or hypothesized as a way for building energy efficiency through actively responding to prevailing climatic conditions including solar radiation, daylight, wind and other factors, and for enhancing indoor environmental comfort levels. However, the climatic conditions will significantly affect the performance of kinetic building envelopes. The following table shows positive (+) or negative (-) affects for each natural source under different scenarios.

<table>
<thead>
<tr>
<th>Climatic variables</th>
<th>Indoor temperature $T_{in}$</th>
<th>Over-low temperature ($T_{in}&lt;T_{λ}$)</th>
<th>Comfortable range $T_{λ}$</th>
<th>Over-high temperature ($T_{in}&gt;T_{λ}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar radiation</td>
<td></td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Air temperature</td>
<td>$T_{out}&gt;T_{in}$</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$T_{out}=T_{in}$</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td>$T_{out}&lt;T_{in}$</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Natural light</td>
<td>$T_{out}&gt;T_{in}$</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$T_{out}=T_{in}$</td>
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<td>+</td>
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<tr>
<td></td>
<td>$T_{out}&lt;T_{in}$</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>

Note: $T_{λ}$ is comfortable range of temperature; $T_{out}$ is outside temperature; $T_{in}$ is inside temperature; + means positive effects; - means negative effects. The “+” or “-” is for general situations of buildings rather than all conditions. Consider natural light, which is generally a positive element for buildings, but it may bring glare problems in some cases. Also, in some cases, the wind flow with higher temperature can still take away the indoor heat in summer.

Based on the above table, we can find the conflicting conditions among four variables when it comes to energy consumption. Under these conflicting circumstances, most common design solutions called passive strategies about building envelopes are not so much “acceptable” but rather “tolerable”. Therefore, the most successful kinetic building envelopes for energy consumption can happen in particular conflicting climatic conditions. Also, the potential of energy savings from BKE systems is determined by whether the site has certain obvious climate conflicting conditions.
Besides the issues of energy, BKE can also relate to inside comfort levels and outside appearance. On one hand, it is apparent that kinetic window shades or blinds in appropriate locations of façades can enhance visual comfort of occupancy and then improve their working efficiency and health status. For example, in the U.S., researchers affiliated with the Lawrence Berkeley for Building Energy have undertaken extensive efforts in studying electrochromic glazing and found it reduced over 12.3% complaints on glare problems (Lee & Tavil, 2007).

On the other hand, the existing studies (Fox & Kemp, 2009) on interactive architecture responding to human behaviors have provided many cases studies for the fact that the kinetic expression of the interactive architecture may carry out more interesting experiences and visual or behavioral interactions with viewers and occupancy.

In addition, in a comprehensive evaluation of the BKE’s performance of a building, all stages of the BKE’s life require considerations. That means the maintenance issues of BKE may have some negative effects, especially on some cases with more complex kinetic motions. There are some failure examples, like the kinetic window systems of the Institute du Monde Arab in Paris, because of its deficient maintenance (Sullivan, 2006).

4.2 Applicability of the PDBIM method

Although the effective simulation methods incorporating with BIM are still pending at the current stage, the PDBIM method shows strong abilities to explore possible shaping and
composing of BKE when it comes to energy issues. Figure 8 shows the mechanism of using the PDBIM method. All variables related to climate, occupancy activities and kinetic components can be connected and visualized by the PDBIM method, as API offers more choices to control complex variables. Also, BIM authorized tools can offer more detailed building information of the parametric model. Consider, for instance in this experimental design, each kinetic panel’s information, which has coordinate, area, height, and others. The parametric information offers other possibilities for analyzing energy or cost. We believe the PDBIM method may become an efficient and effective approach for design buildings with kinetic features related to wind, solar, air, rain and other natural resources for building sustainability.
References


