Design strategies and energy performance of a net-zero energy house based on natural philosophy

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ABSTRACT

This paper presents the design strategies and energy performance of a net-zero energy house (NZEH), Nature Between, which was designed and built to participate in the Solar Decathlon China 2018 competition. The specific parts of the design strategies for Nature Between, including architectural concept, materials, passive strategies and active strategies, are introduced and analyzed. This study includes a discussion of the building’s energy performance based on the measured data gathered in Dezhou, where the competition was held. And also the annual energy simulation using Energyplus software based on the climate of Xiamen, where the prototype was located in. The results show that the design strategies are reasonably applied in Nature Between to achieve the goal of zero energy consumption in Dezhou and Xiamen. Pleasant indoor environment and flexible spaces are achieved in the house using natural material, which embodies the concepts of sustainability and natural philosophy. The practical strategies provided in this paper could help the architecture designs for residential NZEH.

1. Introduction

This paper describes the design strategies of a net-zero energy solar house, Nature Between, which was designed and built to participate in the 2018 Solar Decathlon China Competition in Dezhou. This house is the work of a collaborative team, named Team JIA+, which is made up of students from Xiamen University of China, Team Solar Bretagne of France, and Shandong University of China. Consent agreement was signed by all the groups in the team to clarify the rights and responsibilities of each part. More than 100 students with different majors worked on this project for two and a half years to build a single-family wooden house that combines the traditional Chinese building style with innovative energy-efficient technologies.

The Solar Decathlon competition is an international collegiate competition focusing on solar building technologies, which was launched by the U.S. Department of Energy (DOE) in 2002. Solar Decathlon China 2018 (SDC 2018) was organized by the China Overseas Development Association and Dezhou Municipal People’s Government, with the authorization of the DOE and with the guidance of the Chinese National Energy Administration. It challenged collegiate teams to design, build and operate full-size, solar-powered houses that are energy-efficient and attractive (2018). The scoring system of the competition was divided into ten parts, including five subjective rating items scored by jury evaluation: Architecture, Market Appeal, Engineering, Communication, and Innovation; and five objective items scored by measurement: Comfort Zone, Appliances, Home Life, Commuting and Energy Performance. The scoring system allowed for a comprehensive evaluation of the project from the aspects of design, technology and sustainability.

The term “Zero Energy House” was proposed by Torben V. Esbensen in 1976 (Esbensen and Korsgaard 1977). Since then a lot of studies have been conducted on different aspects of the subject, such as design strategies (Belussi et al. 2019; Fatima, Farouk, and Henry 2018; Longo, Montana, and Sanseverino 2019), new material (Stritih et al. 2018), technologies choices (Feng et al. 2019) and energy performance (Cao, Dai, and Liu 2016). DOE introduced the concept of net-zero energy house and promoted it by hosting Solar Decathlon competitions. The practice of NZEH gradually spread to many areas with different climatic conditions (Lan, Wood, and Yuen 2019; Uk-Joo and Seok-Hyun 2019; Wang, Gwilliam, and Jones 2009).

Because of the comprehensive and interdisciplinary character of Solar Decathlon competitions, many studies were carried out based on the houses built in the competition. Some research papers focused on solar energy technologies, such as new photovoltaic and solar thermal technologies (Aldegheri et al. 2014; Young, Chen, and Chen 2014; García-Domingo et al. 2014; limura, Yamazaki, and Maeno 2014) and building integrated photovoltaic (BIPV) design strategies (Cronenberger et al. 2014, 2014; Chen, Athienitis, and...
Research on the application of energy efficient HVAC equipment (Fiorentini, Cooper, and Ma 2015; Real et al. 2014; Kazanci et al. 2014) and new materials such as PCM materials (Rodríguez-Ubinas et al. 2012; Lin et al. 2014) were also becoming popular. Other studies focused on the integration of various energy efficient technologies (Wang et al. 2009; Peng et al. 2015a; Bohm 2018; Zhang et al. 2014), as well as passive design strategies to reach the net-zero energy goal (Wang et al. 2016; Irulegi et al. 2014; Rezaian et al. 2015; Rodríguez-Ubinas et al. 2014). The performance of Solar Decathlon houses has also been discussed in many articles, including indoor thermal comfort (Brambilla et al. 2017), lighting environment (Berardi and Wang, 2014), energy performance (Cornaro, Rossi, and Cordiner et al. 2017; Peng et al. 2015b; Shrestha and Mulepati 2016) and electrical systems (Iimura, Yamazaki, and Maeno 2014).

Due to the scoring system of Solar Decathlon China 2018, innovation was highly valued. Many new technologies and new materials were used in the competition, and some houses used design strategies to address social problems and reflect regional characteristics. This paper describes the unique approach used by Nature Between to achieve zero energy consumption.

2. Design strategies of nature between

2.1. Architectural concept

Design, preparation, and prebuild of Nature Between were carried out on the campus of Xiamen University. The building area is 138 m², including one living room, one dining room, two bedrooms, one kitchen, one bathroom and one study room on the second floor. The design of the house is based on the climate of Xiamen and the summer climate of Dezhou. It won two of the ten rating items in the competition, namely, Home life and Electric car. Figures 1 and 2 show a photograph and the floor plan of Nature Between, respectively.

The architectural concept of Nature Between is targeted for an old house in an urban or rural village that needs to be transformed into a better living space for a more comfortable life. The proposed base site of the prototype is a traditional Chinese style house near Xiamen University, as shown in Figure 3. This style is named Minnan Dacuo, or quadrangle dwelling, in South Fujian District. A small courtyard lies in the middle of the house, surrounded by four rooms. The main room lies on the north of the courtyard and was retained in the design. By analyzing the relationship between the form of the house and the surrounding environment, it was proposed to demolish the three rooms and the courtyard in the south and build a new house in front of the main room. This new house would share energy, space and social relations with the old one, and coordinate with the surrounding houses. Then, the new house would be integrated with the old one to form a better living environment. The spaces inside and between the two houses would produce diverse spatial experiences for the inhabitants. Figure 4 describes the design process of Nature Between.

The design of the house is based on the concept of natural philosophy, which means that natural
Figure 2. Floor plan of nature between.

Figure 3. Base Site of the Prototype.

Figure 4. Design process for Nature Between. (a) The old house in need of renovation in an urban village. (b) Demolish the three rooms on the south side and build a new house. (c) Lower the roof on the north side and install high windows for lighting and ventilation. (d) Create a gallery yard on the south side of the house for shading and sharing. (e) Install photovoltaic panels on the south side of the roof and create an inner yard in the middle of the house.
resources are used in many aspects of the building. Natural philosophy includes three parts: natural living spaces, natural materials and resources, and natural family relationships.

The architectural design combines a traditional Chinese courtyard with innovative, energy-efficient technologies to create natural living spaces. Similar to traditional Chinese style architecture, courtyards are used in different parts of Nature Between, namely, the gallery yard in front of the house, the courtyard between the new house and the old house, and the inner yard located in the center of the new house. The yards act as green spaces that allow the inhabitants to enjoy nature, and work as buffer spaces to adjust the natural lighting and natural ventilation of the house.

Natural materials are used in most parts of the house. Wood is used as the structural framework and the indoor decoration. Straw is used inside the walls for thermal insulation. Bamboo is used in outdoor folding doors and for shading. Rainwater recycling and water reuse technologies are used for water conservation. A natural and harmonious family relationship is also one of the goals of the design. Several communication spaces in the house are designed to be shared by the inhabitants, such as the dining room, with a large table for eight people, that faces the old house. This room can be used as a dining room and as a sharing space for the family. It is available for the older people living in the old house to eat and communicate with the younger people living in the new house.

2.2. Materials

Materials are carefully chosen for each part of the house to make it more sustainable and easily built by the students. Table 1 presents the structural hierarchies of different parts of the building envelope and their thermal parameters.

2.2.1. Wood

As a traditional Chinese building material, wood is widely used in China and easy to build. To make it easier for the students to build the house, and to avoid thermal bridges, the whole structure is made of wood and OSB panels, which are natural, recyclable, nontoxic, carbon-sink materials. Birch plywood is used for interior finishes, which is more environmentally friendly than PVC materials for a prefabricated building.

2.2.2. Straw insulation

Straw is an agricultural byproduct that is readily available in rural China. Compressed straw panels are used in the building for their good thermal insulation properties and good acoustic performance. They are also cheap, easy to process, and perfectly recyclable. In rural areas of China, straw is usually burned, causing air pollution. However, in Nature Between, straw is compressed into panels without any add-on, which carries no risk to the health of the builders or the inhabitants and is more efficient for fireproofing. Figure 5 illustrates the construction of the timber wall in Nature Between.

2.2.3. Phase change material (PCM)

For the convenience of disassembly and transportation, most houses in the Solar Decathlon use light materials in walls with poor thermal stability. Therefore, the houses have difficulty in resisting the impact of outdoor climate change. To address this problem, phase change materials with a phase transformation point at 23°C are used in the sidewalls of the inner yard of Nature Between. The heat storage capacity of the materials is used to achieve a more stable air temperature in this unconventional yard.

2.2.4. Other materials

Bamboo: Bamboo is used in the folding doors of the gallery yard, which are similar to traditional Chinese-style folding doors, and also as a dynamic shading facade for the building.

Windows: Low-E triple-pane hollow glass is used for the doors and windows of Nature Between. Vacuum glass is used for the two outside layers of the glass, and the hollow layers are filled with argon gas.

| Building component | Structural Hierarchy | U Value (m²·K/W) |
|--------------------|----------------------|-----------------|
| Outside Wall       | 12 mm facing panel + 38*38 mm wool keel + waterproof layer + 18 mm OSB panel + 350 mm compressed straw panels + One-way breathable waterproofing membrane + 18 mm OSB panel + 12 mm facing panel | 0.21 |
| Inside Wall        | 12 mm facing panel + 12 mm OSB panel + 140 mm compressed straw panels + 12 mm OSB panel + 12 mm facing panel | 0.47 |
| Floor              | Waterproof layer + 18 mm OSB panel + 350 mm compressed straw panels + One-way breathable waterproofing membrane + 18 mm OSB panel + 38*38 mm wool keel + 12 mm facing panel | 0.21 |
| Roof               | FRP waterproof + 18 mm OSB panel + 120 mm compressed straw panels + 230 mm glass wool + One-way breathable waterproofing membrane + 18 mm OSB panel + 38*38 mm wool keel + 12 mm facing panel | 0.16 |
| Door and Windows   | Low-E triple-layer hollow glass filled with argon: SL=14Ar+5L+14Ar+5L Inner laminated glass, outside tempered glass, middle 12 mm air layer: 33.2F+12+5H | 0.8 |
| Skylight           | 0.8 |

Table 1. Structural hierarchy of building envelope and the U value.
2.3. Passive strategies

2.3.1. Climate analysis

Figure 6 illustrates the section plan of Nature Between and shows the techniques used in the house. Nature Between is designed by integrating low-tech and high-tech technologies using the key elements of bioclimate architecture, such as shading, natural ventilation, natural lighting, and rainwater recycling. The house is able to regulate its air temperature, humidity, air quality, lighting, acoustic and other comfort aspects in a passive way. The design strategies are based on the climate of Xiamen and the weather in Dezhou in August for the competition.

Figure 7 shows the bioclimate chart of Xiamen and the effects of different passive strategies in this climate. The climate of Xiamen is hot and humid, and in summer the air humidity tends to approach saturation. In order to meet the temperature and humidity requirements of the competition rules, air conditioning is used during the daytime in summer. Passive strategies such as thermal mass and ventilation can be used during the nighttime in summer, so as to reduce the energy consumption of the building as far as possible. Based on the analysis, we used some passive strategies in the house, such as natural ventilation and natural lighting, and two comprehensive strategies, namely, thermal buffer space and dynamic shading.

2.3.2. Thermal buffer space

The design strategy of a buffer space (Dekay and Brown 2014) is used in the inner yard located at the main entrance of the house. The inner yard connects most of the indoor conditional spaces of the house and serves as a thermal buffer between the indoor and outdoor environment. It can be used to adjust the sunlight, ventilation rate and thermal environment inside the house, thus maintaining thermal comfort and creating a good living environment (Figure 8). This space has two glass doors (external and internal) and two skylights that can be opened, closed or shaded according to the weather conditions. It can be used as a sunroom in the winter, heating the indoor air and exchanging heat with the adjacent rooms. In summer, the skylights and the shades are opened to promote natural ventilation and avoid overheating.

2.3.3. Dynamic shading

The climate of Xiamen is hot and humid with high solar radiation intensity in the summer, and the same was true in Dezhou during the competition. To fulfill the indoor thermal comfort requirements in different seasons, three kinds of dynamic shades are used that can be adjusted according to different climatic conditions.
Nature Between has a double layer roof, the upper roof stretching out at the south loggia to provide shade for doors and windows. Electric shading louvers are used in the roof, the angles of which can be controlled by the occupants to control direct solar radiation based on different weather conditions (Figure 9).

Bamboo doors are used in the south facade, forming a distinctive light and shadow effect. They can be folded similarly to traditional Chinese style doors and are used as a dynamic shading facade to control direct solar radiation. They can be opened for sunshine and a better view during the winter season, and can be closed for shading in the summer.

Shading screens are installed on the skylight in the inner yard and the north side windows on the second floor. When the solar radiation intensity is too high, the electric sunshade roller curtains outside the skylight can be closed to achieve a better shading effect, which can also be controlled easily by an intelligent control system.

2.3.4. Natural ventilation

Natural ventilation can remove heat and humidity from the house and improve indoor thermal comfort conditions when the outdoor climate is comfortable. This is particularly important in the climate of Xiamen and is also an important factor for thermal comfort control.

The chimney effect is used to promote natural ventilation in Nature Between. The height difference between the ground and upper floors, and the air temperature difference due to the greenhouse effect

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Figure 6. Section plan of Nature Between.

Figure 7. Bioclimate chart of Xiamen and the effects of passive strategies.
in the inner yard, both help to create a chimney effect, which can be used during the mid-season and summer days with comfortable outdoor wind conditions.

Some windows can be controlled by the intelligent control system in Nature Between, such as the skylight in the inner yard and the north side windows on the second floor. They can be controlled together with the HVAC system to regulate the indoor thermal environment.

2.3.5. **Natural lighting**

The design of natural lighting is also an important issue in Nature Between. Lighting design is based on the simulation results to guarantee a daylight level of 300lx for the main accommodation rooms. The lighting level inside the house can be regulated through the dynamic shading systems to ensure indoor lighting comfort. The kitchen does not have enough natural light because its windows are shaded by the outside.
corridor. To compensate, a solar tube is used in the kitchen to increase natural lighting.

2.4. Active strategies

2.4.1. BIPV system

Solar panels are the only energy source in the competition, so BIPV design is especially important for the house. Fifty-four photovoltaic panels and two solar thermal panels for water heating are installed on the roof of Nature Between, emphasizing the design concept of building integrated photovoltaic systems. Each PV panel has a rated peak power of 285 Wp, so the total rated power of the solar panels is 15.39 kWp. The conversion efficiency is 17.50%. The PV panels are installed on the south roof and are inclined to the horizontal surface at an angle of 20 degrees, which takes into account the best orientation during the summer and can produce enough energy to balance house energy needs during the competition.

There is a 150 mm ventilation layer between the upper PV panels and the roof, which can take away the heat inside the layer to cool the roof surface. As the generating efficiency of the PV panels increases when the temperature drops, this design can also improve the efficiency of the PV system.

2.4.2. HVAC system

The HVAC system is critical in the design of zero energy buildings, because normally its energy consumption accounts for 50% to 70% of the total power consumption of the house, and it affects the indoor comfort and air quality directly.

In Dezhou, the outdoor temperature varies from −15°C to +35°C and the humidity level usually is very high in the summer. In response to the weather conditions, two individual devices, the air conditioning system and the fresh air system, are used in the HVAC system to control the indoor parameters independently. Air temperature and humidity are controlled by the air conditioning system. A reversible heat pump is used in the air conditioning system to produce heat in the winter and cool air in the summer, with a rated cooling capacity of 8.8 kW. The fresh air system, with an air change rate of 0.5 ach, is used to control the indoor CO2 level to maintain healthful air indoors and to control the PM2.5 level in the house.

The HVAC system is installed and connected through the attic of the north roof. Four fan coil units are used for the living room, the dining room and two bedrooms, and can be controlled separately for each room. Fresh outdoor air is disposed by the air handling unit and the air conditioning equipment and then sent into the room.

2.4.3. Control system

An intelligent control system which supports the KNX protocol is used in the house to control the active equipment and many parts of the facade for shading and ventilation. The aim of the automated systems is to integrate the passive systems such as the dynamic shading, and the active systems, such as the HVAC equipment and the electrical appliances, to reach the comfort level specified in the competition rules and to allow the building to consume less electricity than it generates. Balancing the building’s energy consumption and power generation is the goal of optimization.

The energy consumption of the appliances is measured and controlled through KNX communication (Figure 10). This protocol is open and
interoperable. Specialized equipment, such as the heat pump or the charging station for electrical vehicles, communicates through different protocols. All the collected information is centralized on a server for processing and used on the building. The intelligent control system makes the house a smart home by informing the inhabitants of the operating status of the equipment and by controlling them based on the different requirements.

3. Energy performance of the house

3.1. Tasks of measurement in the competition

After two and a half years of preparation, Nature Between was transported to Dezhou in the middle of June 2018. After 20 days of intensive construction, the final on-site tests were taken from August 2nd to August 16th. Table 2 shows the tasks in the competition. Different tasks followed different schedules. Environmentally related data were collected in the Comfort Zone contest for temperature, humidity, CO2 level and PM2.5 level. Energy data were tested in the Energy Performance contest for Energy Balance and Generating Capacity. In the Comfort Zone contest, three sensors were provided by the committee and placed in the living room, in the south bedroom and in the second floor bedroom. Environmental data were collected during the entire competition, except when the public exhibit was ongoing.

During the measurements, contests and tasks were carried out simultaneously inside the house, so the team had to prepare carefully for every task to minimize the influence on the environmental measurement.

3.2. Climate data and energy performance of nature between during the competition

Outdoor climate data during the competition were measured using a meteorological station by the team. Outdoor air temperature, humidity and solar radiation during the competition were analyzed.

Figure 11 shows the indoor and outdoor air temperature during the competition, and Figure 12 shows the indoor air humidity.

Solar radiation intensity on the competition site was measured by a meteorological station from August 2nd to August 16th. It was sunny and extremely hot during those days, except for a heavy rain on August 14th. The outdoor air temperature often exceeded 40°C at noon and 30°C at night, and the air humidity was also very high. Thus, a great deal of heat had to be removed to reach the 22-25°C indoor temperature standard of the competition. The HVAC system was used together with passive strategies, such as using dynamic shading to reduce heat gain from solar radiation and opening the skylight of the atrium for ventilation at night.

3.3. Annual energy simulation for nature between in the xiamen climate

Because the design of Nature Between is based on the climate of Xiamen, the year-round climate adaptability of the house in Xiamen also needs to be analyzed. This analysis is based on Energyplus software to simulate Nature Between’s energy consumption. An analysis model was built and set based on the detailed size, construction and task schedules of the house during the competition. Heat gains, PV generation and energy consumption balance of the house were analyzed.

The energy consumption data during the competition were recorded and compared to the simulation data, which are shown in Figure 15. We can see that the simulated data are basically consistent with the measured data. There are also some differences between the two sets of data, because many tasks were carried out each day during the competition and it is difficult to simulate all these tasks. Based on the method in ASHRAE Guideline-14a, the CV (RMSE) (coefficient of variation of the root-mean-square error) of the simulated data is 14.6%, and the NMBE (normalized mean bias error) is 1.6%, which meet the requirements (30% and 5%, respectively, for hourly calibration). Therefore, the model is acceptable for energy simulation.

Then, this model is used to study the annual energy balance of the house in the climate of Xiamen. The parameter settings of the model are shown in Table 3.

The monthly energy balance data are shown in Figure 16. The cooling load of the house is 70.0 kWh/(m²*a), much higher than the heating load, which is only 3.5 kWh/(m²*a). The influencing factors for cooling load are equipment, infiltration, solar, mechanical ventilation and people, from large to small respectively. The lighting load only accounts for a small proportion of the cooling load, and in winter it is beneficial to reduce the heating load. Infiltration and mechanical ventilation (fresh air) increase the cooling load in the summer and increases the heating load in the winter.

Figure 17 shows the simulated monthly PV power generation and the monthly building energy consumption of Nature Between in Xiamen. Except for July and August, the PV generation always exceeds
electricity consumption. Total annual consumption is 12,544.9 kWh, which is only 75.6% of the 16,590.5 kWh generated by the PV panels. We can calculate that 11.6 kW of PV installation is enough to meet the house’s energy balance in Xiamen.

Figure 18 compares the monthly heating and cooling loads of Nature Between in Xiamen with and without dynamic shading. The model was set according to the actual situation of the dynamic shading system. The shading louvers, the bamboo doors and the shading screens were controlled according to solar radiation intensity and outdoor air temperature. The simulation results show that the annual thermal load can be reduced by 17.4% under the condition of dynamic shading, compared with the condition of no dynamic shading. The energy saving benefit of dynamic shading is significant in summer, but it slightly increases the heat load in winter.

### 3.4. Lessons and recommendations

Despite the good results obtained in the competition, the experiences gained from the measurements indicates that the design strategies of Nature Between could be improved in several aspects:

1. Although there is good thermal insulation in the walls, windows and doors of Nature Between, the airtightness of the walls is not good enough because of the prefabricated construction method. The installation of some pipes, such as the solar tube installed on the roof of the kitchen, forms thermal bridges on the building envelope. Therefore, these parts of the building should be well insulated to avoid heat loss and air infiltration.

2. The living room is 6 meters high and connects to the dining room and the second floor room, resulting in a large volume and excessive air conditioning energy consumption. If this space were divided into several small rooms and controlled independently, then energy consumption could be reduced.

3. Because the air temperature varies greatly in Dezhou, it is better to use a VRF (Variable refrigerant flow) air conditioning system in the house. This system can better adapt to the changing cooling.
Figure 11. Air temperature during the competition outdoors, inner yard and dining room.

Figure 12. Humidity during the competition.

Figure 13. Solar Radiation Intensity and Generation Power of PV Panels during the Competition.
or heating loads and achieve better energy efficiency.

4. Conclusions

By analyzing the design concepts and energy saving technologies of Nature Between, this paper exhibits a method of using comprehensive strategies to achieve the goal of zero energy consumption in buildings. The practical strategies provided in this paper could help architecture designs for residential NZEH.

According to the measured and simulation data, the following conclusions can be drawn:

(1) The natural living spaces, natural materials and natural family relationship in Nature Between embody the design concept of natural philosophy. The measured results show that passi and active design strategies are reasonably applied in Nature Between to achieve the balance among function, aesthetics, comfort and energy.
(2) The results shown that the Nature Between can generate more electricity than its demand during the test in Dezhou. There was a 37.0 kWh PV generation surplus for Nature Between during the competition in Dezhou.

(3) The annual simulation results shown that Nature Between is able to achieve NZEH in Xiamen. The simulation results show that the total annual consumption for the house is 12,544.9 kWh in Xiamen, which is only 75.6% of the 16,590.5 kWh generated by the PV panels.

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