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Typological Evolution of High-Rise Buildings in Terms of Thermodynamics and Energy Formation

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Abstract

High-rise buildings are frequently criticized for their absolutely artificial environments and high energy consumption. This paper tries to present an alternative approach to, and new prototypes for high-rise buildings through dialectic reconsideration of the responsive relation between high-rise buildings and environmental elements, in terms of thermodynamics and energy formation.

Keywords: Thermodynamic, Energy formation, High-rise buildings

Preface

What would happen if for a moment we suspended gravity, and with it, the tectonic traditions controlling the design of modern high-rises? What would happen if we forgot the fixed image of skyscrapers and revaluated it exclusively based upon thermodynamic criteria?

Inaki Abalos, 2014

1. Thermodynamics and the Issue of Energy Formation

In the face of energy crisis, global warming and environmental deterioration since 1970s, the autonomy of buildings is confronting unprecedented challenges as well as excellent opportunities that have already raised public awareness. As a focal point in the light of the current situation, energy is becoming one of the most prevailing and essential topics among architects.

Just as the Germany philosopher Friedrich Nietzsche's definition, the world is a monster of energy that cannot be generated or lost, but only transferred. When energy passes, as work, as heat, or with matter, into or out of a system, its internal energy changes in accordance with the law of conservation of energy. The first law of thermodynamics goes beyond a purely physical description of fundamental physical quantities. Defining the energy formation of buildings, the thermodynamics law will be regarded as a primary design principle in the typological evolution of modern high-rise buildings affecting flow and configuration in buildings. Architecture in the twenty-first century is no longer a matter of inventing visual forms, but of capturing non-visual forces such as energy.

Accounting for almost 40% of the energy consumption around the world, buildings, especially high-rises, as majors consumer of energy, are at least partially responsible for the worldwide energy crisis. High-rise buildings are ineffective in energy use because of their huge mass, their superlative height and hybrid programs, which lead to unexpectedly high capital and operational expenditures. Nevertheless, high-rise buildings still have great potential to be shaped according to their external climate situation, internal space requirements and energy flow between these two environments, for the same reason.

Firstly, due to their many external surfaces, high-rises are exposed to the climate and surroundings to an great extent, which provides an excellent opportunity to set up an interactive connection with the environment.

Besides, on account of their great height, wind impacts more on high-rises than lower buildings. Therefore, a reasonably-shaped form will not only conserve material used for carrying a structure's lateral load, but will also provide comfortable cross-ventilation to the interior and improve stack effects to cool down the building.

On the other hand, enormous mass and density lead to the fact that hybrid programs co-exist in one single tower, which makes high-rise buildings look like symbiotic ecosystems. As each part of the program is different in thermal performance, chances are, if the location and area of those programs are well-organized and some high-performance air/water distribution systems are adopted, the energy flow in high-rise buildings will balance internal heat and lead to thermal comfort for human beings.

The study of energy is not just a further research of

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advanced technology, nor does simply it represent a technical burden to be overcome. It should be a holistic consideration of a comprehensive knowledge, design, construction and operation process, which can help architecture achieve its final optimum allocation of form, space, program and system.

Designers of current high-rise buildings rely too much on artificial mechanical equipment and neglect the connection between internal systems and external surroundings, isolating high-rises from energy flow and the environment. This steady and closed boundary condition cannot meet the requirements of future buildings and cities.

If the relationship between energy and architecture can be re-considered, then a new system of high-performance buildings can be formulated, which is called the thermodynamic system: an open system that can respond to exterior and interior surroundings. In this new system, the current strict hermeticity of buildings will be dissolved, and the line between the natural and the artificial will become blurred.

2. Strategies of Energy Formation

Skyscrapers have massive potential to increase energy efficiency and be shaped by energy. Using the forces of energy as design tools, energy formation, which is based on the study and analysis of thermodynamics laws and energy flows, can better motivate the shape of high-rise buildings through energy capturing, energy programming and energy channeling. The concept of energy flow is proposed by the founder of modern ecosystem ecology, Howard Thomas Odum, who drew this idea from Alfred J. Lotka's maximum power principle and refined it. His study on ecosystem is implemented by Diagram Energy Flow and Energy Diagram.

2.1. Form and Environmental Elements: Energy Capture

Attitudes about external energy, generation, and conventional graphic composition in architecture design are usually completely distinct.

The old-fashioned approach to building shaping and façade design is dedicated to protecting buildings against the impact of the exterior environment and solar energy, such as redundant heat, unacceptable air flow and glare pollution. It is a virtue of mechanical systems that a comfortable but isolated and closed micro-indoor environment can be created, which tends to consume more energy resources.

In contrast, energy formation is meant to take advantage of energy that already exists in the environment. Energy capture includes cross-ventilation, solar thermal and natural daylighting, as well as the transformation of on-site solar energy, ground-source and wind power. In order to achieve the proper energy-capturing effect, building forms need to be designed as driven and motivated by climate. Adaptive facades need to rebuild the connection between buildings and energy, allowing the passage of sunshine and air. On the other hand, a continuous energy-distributing interactive space needs to be wrapped around the building space, ensuring the energy that is transferred will be used immediately after it is captured.

The major approaches of energy capture include radiation, conduction, convection, infiltration and internal gain. Radiation generally refers to solar irradiation, which accounts for the largest proportion of energy captured. By adjusting mass orientation, exposed surface areas and angles of the components attached to the façade, façade isolation, daylight distribution and photovoltaic efficiency can be optimized. Therefore, the energy-capture capacity can be improved. On the other hand, as to some internally-dominated buildings such as commercial high-rises, people, lighting and equipment will consume huge amounts of energy, which should not be ignored during planning for energy-generating buildings.

2.2. Space and System: Energy Programming

Due to the enormous density and mass of high-rises, like a symbiotic ecosystem, hybrid functions overlap in one single tower, which has become practically inevitable in dense cities since the late nineteenth century. In the light of energy, the mixed-use building is not just a sum of different programs. The relationships among the ostensibly chaotic elements have to be explored to make each part of high-rises incorporate better.

The Downtown Athletic Club in New York City was a typical example of the hybrid. In this building, components, such as the hall, the bowling alley, the gym, the pool, several game rooms, private dining rooms and club offices were arranged in the same space or stacked up. These spaces were blended together (Fig. 1).

Each part of the high-rise has a distinct energy-use schedule. Generally, the peak load in offices appears between 9 am and 3 pm. As to gyms and residential areas, the inverse condition requires extra energy storage. With smart load management and energy storage strategies, such as thermal massing and phase-change materials, this schedule of diversity will lead to higher efficiency in energy use.

Each part of the high-rise has a different thermal performance. For example, offices and gyms will generate enormous internal heat, while lobbies and apartments tend to absorb it. If the location and space of those components are well-organized and some high-performance air/water distribution systems are adopted, energy flow in high-rise buildings will balance the internal heat and lead to thermal comfort for human beings.

Moreover, each part of the high-rise has completely different requirements of luminance. For example, open offices need diffused, rather than direct light. In comparison, completely natural daylight is preferred for residential spaces. On the contrary, some presenting rooms have

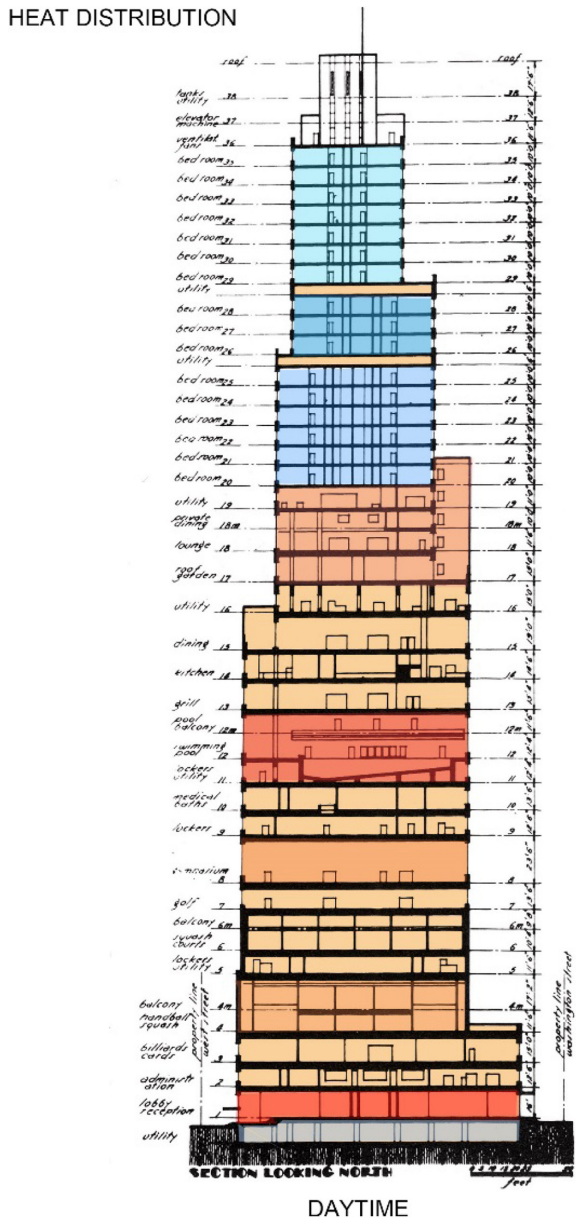


Figure 1. Heat distribution of Downtown Athletic Club. https://www.pinterest.com/pin/63754150950426528/, Revised by the author.

to be protected against any kind of excessive light. If the façade composed of shades and light shelves can be modified properly, a better performance of daylight distribution will demonstrate more diversity, which can perfectly meet those varied requirements.

2.3. Formation in Urban Scale: Energy Channeling

The prevalence of urban agglomerations requires all buildings on campus to be seen as a complete synergistic system. Energy not only flows in a single building, which is related to the internal space configuration, but is also channeled from one building to the other. Therefore, more attention needs to be paid to the relationship between energy flow and urban design. Closely analogous to a symbiotic artificial ecosystem, energy channeling involves holistic consideration of air flow environment, solar conditions and energy sharing among buildings. For example, an optimized master layout can block harsh wind and maximize solar distribution in winter, as well as increase air velocity and cast adequate shadows in summer.

Energy capture is a new attitude toward energy in architecture design. Through the optimization of mass, orientation and environmental elements, more energy can be generated through the interface of a building. Energy programming is a new strategy to balance energy within a single building, which is affected by function, configuration and system organization. Energy channeling is a similar strategy to balance energy among buildings at larger scales, which involves the master-planned layout of a group of buildings. This new approach of energy synergy and formation will contribute to a typological evolution and innovation of high-rise buildings in an embrace of thermodynamics.

3. Typological Evolution of High-rise Buildings based on Energy Formation

Energy formation based on thermodynamic laws is becoming a critical methodology in both academic circles and professional practices.

3.1. Energy Capture: New York Solar Interface & Chicago Research

Located in New York City, this climate-adaptive and energy-symbiotic building aims to achieve a delightful climate resource on-site, such as solar and air flow, through the energy formation of a continuous perimeter buffer zone to reduce internal energy consumption, generate more renewable energy and create an acceptable semi-outdoor space for people (Fig. 2).

The first step of this design is to guarantee that the exposed surfaces of the building can secure as much on-site energy sourcing as possible. Retaining the basic box shape, massing and orientation maximizes annual solar irradiation and exploits surplus natural daylighting, thermal energy and photovoltaic generation (Fig. 3).

The building envelope in the project is treated as a buffer zone and a connection bridge between exterior and interior environments. It is no longer a conventional single-layer skin but a more complex and multi-layered ecosystem. The façade is composed of two layers, with an air cavity in between. The purpose of the exterior layer is to capture solar irradiation through clear laminated glazing, with reasonable installation tilt and azimuth. The interior layer needs to guarantee that the energy captured by the first layer will be used properly. Through daylight control components, thermal control materials and airflow control configuration, the filter face can select the right amo-

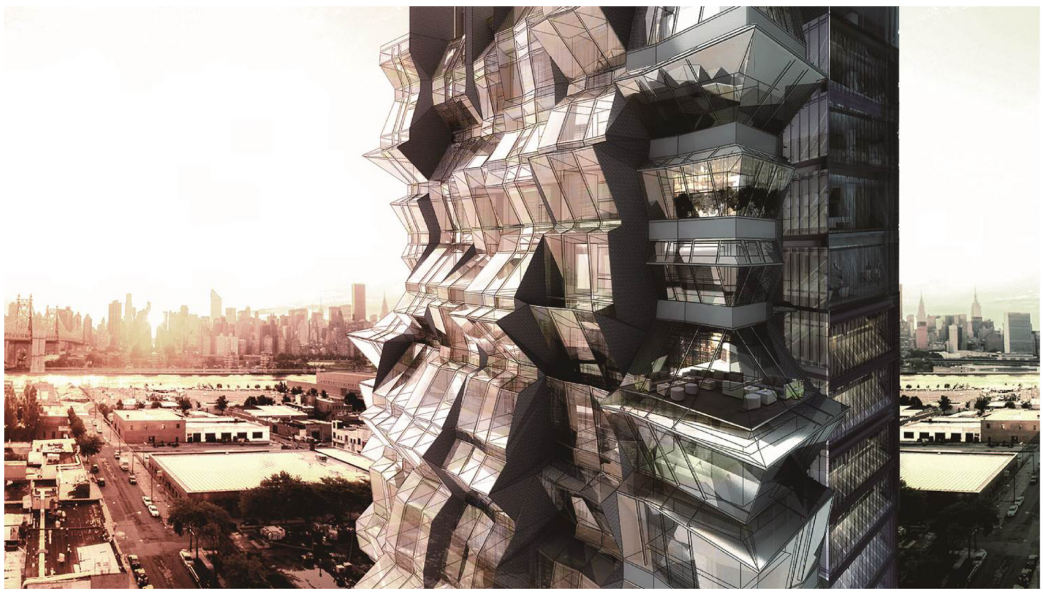


Figure 2. Solar interface. Supplied by Xiaofei Shen, students' studio work in CASE.

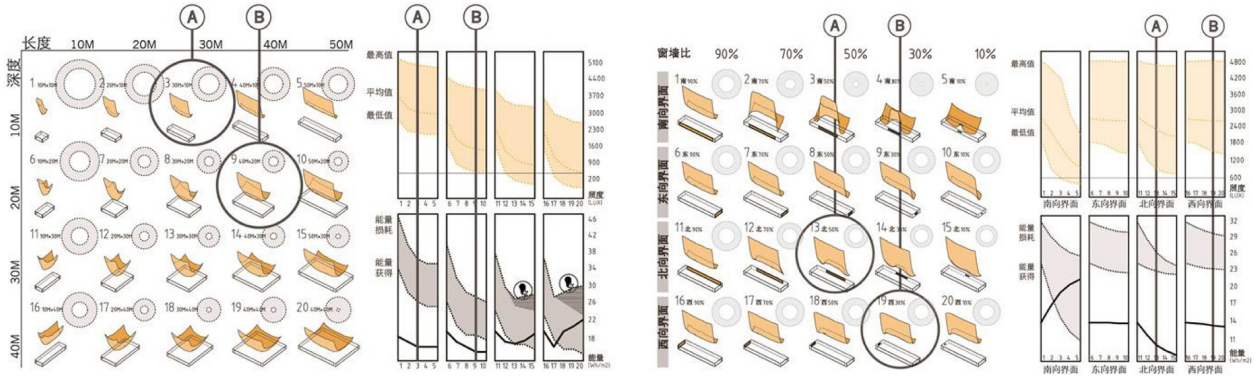


Figure 3. Parameter control of the surface. Supplied by Xiaofei Shen, students' studio work in CASE.

unt of energy at the right time according to the occupants' needs.

The air cavity is also installed as a building-perimeter buffer zone for distributed systems, and as a secondary programmatic space, accessible by occupants. This is a major space where the energy captured can be reorganized for different uses. Shades, light shelves, reflectors and PV panels inserted in this continuous cavity are of different sizes, angles and locations, which can help to improve building performance. Through computer-based performance simulation and multi-objective trade-off optimization, these panels can bounce more solar rays to augment the indoor illuminance level, protect against overheating by casting proper shade, and generate electricity through an integrated PV systems. More importantly, this customized façade system creates a kind of diversity and flexibility in indoor daylight distribution and energy transformation, which can perfectly meet the various requirements in illuminance level and energy use in each part of the building. In addition, people can also step into this comfortable and delightful space to enjoy natural sunshine and breeze.

Other forms of energy, such as the flow of water, can also be captured with the help of building energy formation. A Chicago project focused on the issue of collecting rainwater and reusing graywater. Rainwater was collected through the architectural façade (Fig. 4). The façade was divided into small "holes". Each "hole" would catch the rain or fog and let it flow into the water tank in the middle of the tower. All in all, the project turned the façade, the form and the structure into energy-capturing tools (Fig. 5).

The shape was determined according to climate data, including the rainfall capacity and wind direction in Chicago. The tower was twisted so that it could reduce tur-

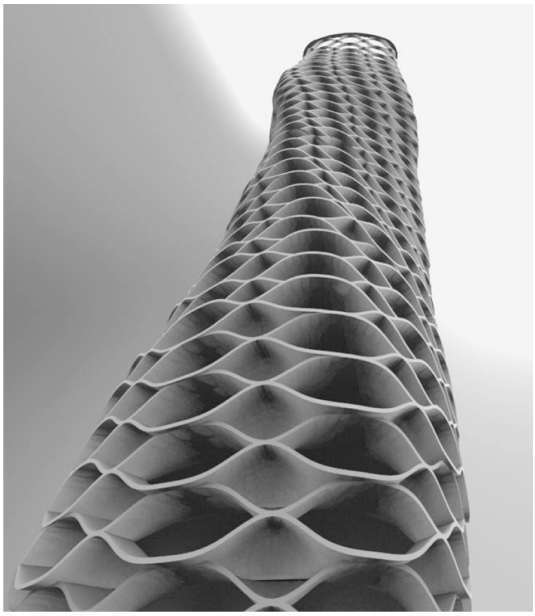


Figure 4. The façade for capturing rainwater. Supplied by Linxue Li, students' studio work in Tongji University, Supervisors: Linxue Li, Antoine Woods, and Zhendong Wang etc..

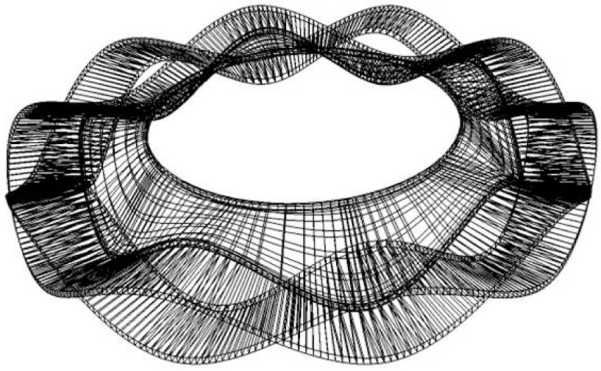


Figure 5. The unit of the capturing tools. Supplied by Linxue Li, students' studio work in Tongji University, Supervisors: Linxue Li, Antoine Woods, and Zhendong Wang etc..

bulence in the windier areas. The vertical section was arranged according to function, each of which has different demands for water in terms of quantity and purity. The water flows downwards and can be reused. A collection-purification-reuse system for rainwater would be created to capture energy.

3.2. Energy Programming: RB05 High-Rise Cluster in North Hexi New District, Nanjing

This project aims to reflect on modern skyscraper forms and introduce a design concept of an energy formation typology based on thermodynamic principles. The project has a mixed-use program. There are four residential towers, in addition to the tallest tower, which contains a hotel, convention center and retail space at the base. The hybrid functions overlap in one single tower according to the concept of energy programming (Fig. 6). The architect created two “energy rings” in the taller tower. One is between the “energy-producing” and the “energy-consuming” programs. As mentioned earlier, each part of the high-rise is different in thermal performance. According to the principle, the architect defined the market, the convention center, the gym and the restaurant as the “energy-producing” programs. On the contrary, the hotel and the office were defined as “energy-consuming” programs. Balance is attained and the energy flow in the high-rise buildings is realized through overlapping the two kinds of programs. The atrium works as the medium for energy exchange, so the heat can be transferred from the heat producers at the podium, upwards to the residences.

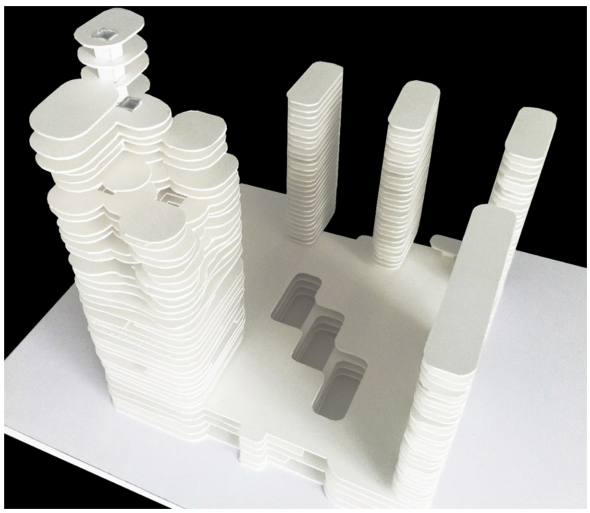


Figure 6. The high-rise cluster with five towers. Supplied by Linxue Li, works of ABALOS+ SENTKIEWICZ & Atelier L+.

Another ring is set between the building envelope and the exterior climate. The hotel rises up in a compact volume and tapers into smaller units. The curtain wall works as the exchanger between the interior and the exterior. At some special levels (such as the convention center and the hanging garden), there are air intakes set up to control radiation and the ventilation. The in-curved curtain wall of the smaller units can accelerate the ventilation rate so as to absorb more fresh air into the atrium. The greenery on the roofs of the units can prevent excessive solar irradiation in summer. Thus, the tower works as an open system that communicates with the exterior environment just like a symbiotic system (Fig. 7).

3.3. Energy Channeling: High-Rise Cluster in Zhongfu Square, Yiwu

The project of urban agglomeration located in the Cen-

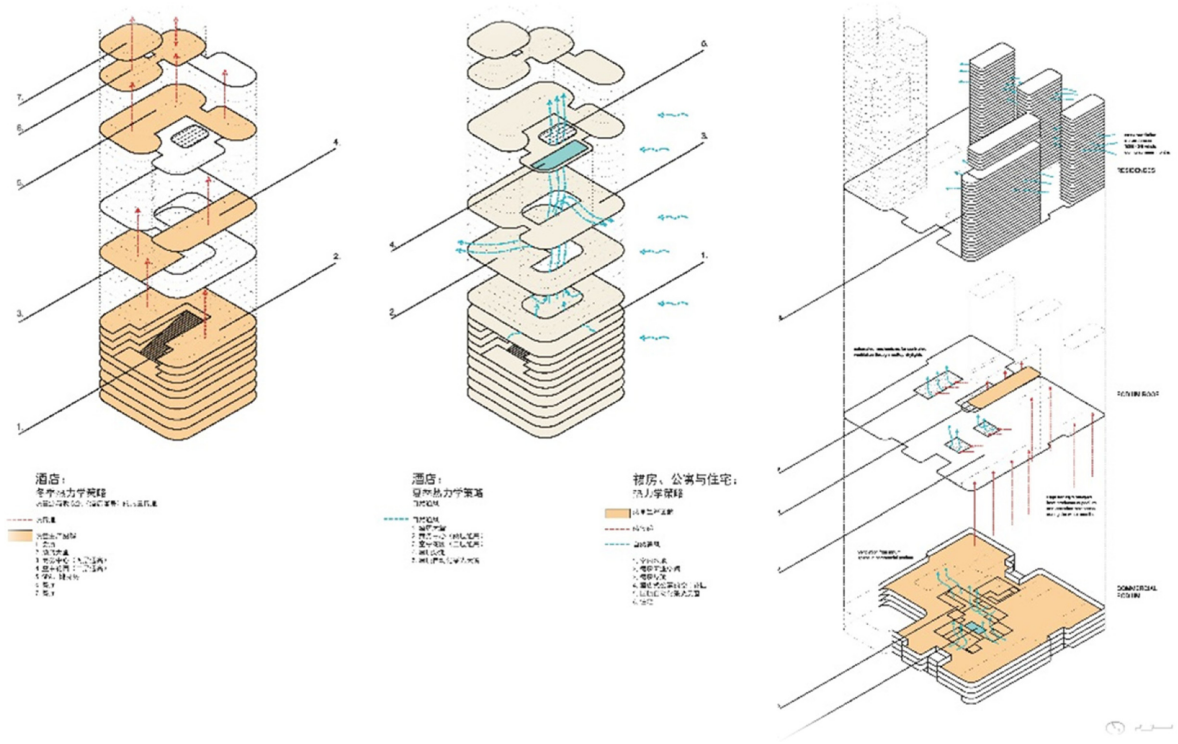


Figure 7. Two energy "rings". Supplied by Linxue Li, works of ABALOS+ SENTKIEWICZ & Atelier L+.

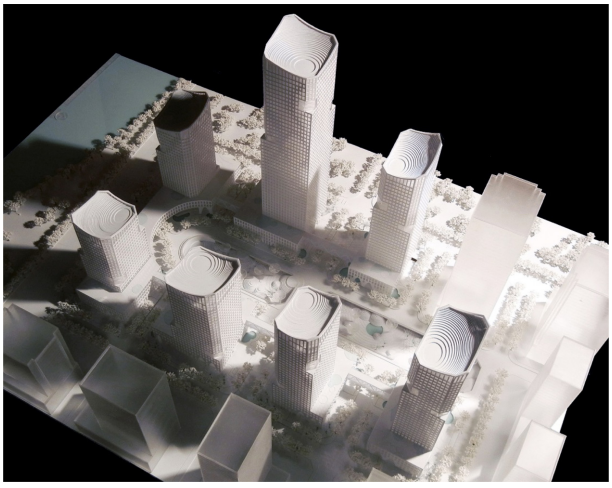


Figure 8. The high-rise cluster in Yiwu. Supplied by Linxue Li, works of ABALOS+ SENTKIEWICZ & Atelier L+.

tral Business District (CBD) of Yiwu can be used to interoperate the mechanism of energy channeling (Fig. 8). At the beginning of the project, the architect had an overall consideration of the site and used computerized analysis to determine how best to capture the energy flow of wind, light and heat. Then, the energy flow between the building blocks could be reflected in the master plan. In this project, eight towers and a landscaped central square composed the urban agglomeration based on the relationship between building forms and the exterior climate. The square inserted in the center of the building cluster not only provided urban space for the public, but also brought more light and ventilation to the buildings in the project. The volume is taller in the north, so as to block cold winds in winter. On the contrary, the smaller volume in the south can let in the wind to cool the square. The corner of each volume is chamfered to reduce turbulence in windier areas, so the expense of cooling and heating consumption can be cut down (Fig. 9). The bent roof, which comes from the traditional Chinese roof, has more surface area with which to capture solar radiation, and can also be used to collect rainwater. With the regulation of the energy channels inside the conglomerate, the clusters work as a complete synergistic system in Yiwu's subtropical climate conditions.

4. Conclusion: Fexploration of New High-rise Typologies

In the field of architecture, research on tectonics and energy almost share the same history, in which one is visible but the other is invisible; one is fully developed but the other is neglected. Nowadays, due to increasing the global climate change, energy crises and broader environmental and social issues, energy, the invisible substance, is being refocused. The construction of new knowledge systems that integrate architectural ontology and

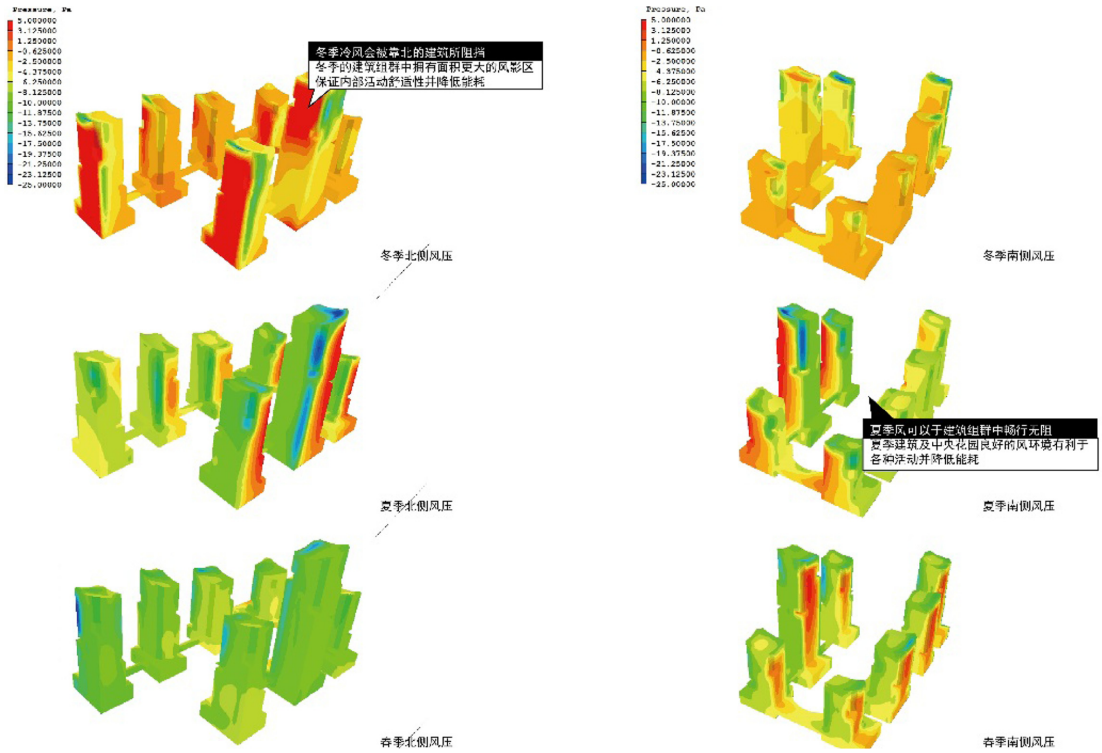


Figure 9. Wind analysis of the high-rise cluster. Supplied by Linxue Li, works of ABALOS+ SENTKIEWICZ & Atelier L-

tools will provide the architect an opportunity to regain the power in a wide range of discourse on sustainable issues. Thermodynamic architecture associates energy flow and architectural form generation together. It has put forward a new concept of energy matters and rethinks the interaction of energy flow, climate response, environmental performance, perception and experience, and architectural ontology. It goes beyond the empty promises and assemblage of technologies in the field of "sustainable building," and instead explores a contemporary, innovative architectural paradigm, through the integration of thermodynamic technological frontiers and architectural forms.

Acknowledgement

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