Research on the Technical Path of Concrete Building to Net Zero Carbon Pre-fabricated Pre-finished Volumetric Modularization

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Abstract—Global demand for livelihood buildings is still strong, and construction in the traditional way will continue to increase CO₂ emissions. The COVID-19 epidemic has led to a shortage of construction personnel sent overseas, and the transformation of the construction industry to a mechanized, prefabricated and digital construction model will alleviate these problems. The paper will develop a low-cost, industrialized, integrated precast and decoration concrete volumetric modular integrated net zero carbon emission building technology mode based on the whole building life cycle evaluation method. This building module product has various functions of zero carbon building at the beginning of the design, and it constitutes zero carbon building after on-site assembly. This technical system has higher production efficiency and better process quality than cast-in-place concrete buildings, and reduces construction time, cost, waste, on-site safety risks, noise and dust. It is the best choice of concrete building to pre-fabricated pre-finished volumetric construction technology transformation, is the construction industry to help "Two carbon" climate goal to achieve one of the green technology path.

1. Introduction

About 51 billion tons of greenhouse gases are emitted into the atmosphere each year, and the ecological damage and environmental pollution caused by global warming have had an irreversible and catastrophic impact on people's lives and health. According to statistics, in 2018, China's carbon emissions from construction accounted for 51.3% of the national carbon emissions, the carbon emissions from the production stage of building materials accounted for 28.3%, the carbon emissions from the construction stage accounted for 1%, and the carbon emissions from the construction operation stage accounted for 21.9%[1].

Traditional concrete buildings are cost-effective, strong and durable, but there are also problems of low assembly rate, long construction period, large error, bad construction environment, high operation risk, much construction waste and environmental pollution. Compared with the traditional
construction mode, the energy consumption of industrial construction is reduced by 20~30%, the material loss is reduced by about 60%, and the construction waste is reduced by 83%[2]. Many countries have carried out the research of pre-fabricated pre-finished volumetric construction buildings and accomplished the construction of a number of demonstration projects. In 2019, Singapore built two 40-storey towers of a fully concrete precast building system, with 1,999 precast modules ranging in weight from 37,000 pounds to 64,000 pounds[3]. However, Limited by the installation of connecting nodes, the existing concrete modular buildings cannot realize the overall prefabrication of interior decoration, and there is a lack of research on the technical system integrated with the green zero carbon building technology.

To achieve the Chinese government's goal of carbon peak by 2030 and carbon neutrality by 2060, carbon emissions should be carefully managed throughout the life cycle of buildings, from design to construction and operation. The market is in urgent need of research and development of low-cost pre-fabricated pre-finished volumetric construction modular products that integrate low carbon and negative carbon functions, so as to achieve the realization that the low carbon performance can be controlled when prefabricated in the factory. The building assembled by the assembly and fixation of standard modules is a net zero carbon building.

This paper will study the material saving of pre-fabricated pre-finished volumetric modular building structure, material saving and process saving in the production process, carbon reduction in the overall assembly and demolition construction process, and net zero carbon path in the operation process of modular building, and is not included in materials, structures, equipment and intelligent building technology itself.

The results of this study will promote the development of the construction industry in the direction of ecology, health, energy security and internationalization, high quality, and drive the output value of 100 billion net zero carbon, modular prefabricated buildings. The application and promotion of the research results is conducive to the increase of new jobs and the sustainable development of the ecological environment, which is of great significance to the harmonious coexistence of human beings, buildings and the earth!

2. Carbon reduction path of pre-fabricated pre-finished volumetric construction member structure

2.1. Standardization, modularization and menualization of pre-fabricated pre-finished volumetric construction module

Standardization and modularization of the pre-fabricated pre-finished volumetric modules are conducive to the industrial batch production of module products, the connection of modules and other products to form new modules or series products, the versatility of module products, the reduction of material waste and the improvement of production efficiency in module production. Through the investigation of existing room types, equipment, modules, etc., the core module size is formulated, as shown in Tab.1.

| Tab. 1 Dimensions of basic modules |
|-----------------------------------|
| Any Combination                   |
| Optional room (m)  | 3 | 3.3 | 3.6 |
| Optional depth (m) | 5.1 | 6 | 7.2 |
| Optional height (m) | 2.7 | 3 | 4.5 |

Integrated construction of building operations and decoration can save construction time and reduce the pollution and material waste caused by on-site decoration. Menuization allows customers or owners to select their favorite functional modules (living room, bedroom, kitchen, etc.), basic module sizes (see Tab.1), additional modules (balcony, air conditioning, sun visor, etc.), decoration modules
(atmosphere, materials, furniture, etc.), and equipment (heating, home appliances, intelligence, etc.) during building planning. The effects on reducing carbon emissions are:

1. The products of the module factory intervention in the architectural design and the direct transferring from the model library can save a lot of design time.

2. AI design software can generate several building design based on the size of the modules, rather than taking the time to break the building down into prefabricated parts at the construction drawing stage of the building design. Thus reducing the carbon emissions of the design process.

3. To avoid the owners do not like the unified decoration style, demolition and transformation into waste.

4. After receiving construction orders, manufacturers in the upstream and downstream industry chains can be organized to process the products in accordance with standardized designs, and then shipped to the main factory for assembly and installation.

2.2. Monolithic reinforced concrete structure of pre-fabricated pre-finished volumetric construction monomer

The Pre-fabricated pre-finished volumetric construction modular building has a unique structure that uses less concrete than conventional buildings. The Pre-fabricated pre-finished volumetric construction module is a precast reinforced concrete unit with a roof, bottom plate and four walls. The modular wall structure is similar to the concrete shear wall structure, the steel mesh and concrete are connected to the top and bottom plate as a whole nonlinear deformation of the skin structure. A single module itself is a load-bearing component, which can withstand the vertical and horizontal loads transmitted by other modules and by itself. Therefore, the thickness of concrete wall (as shown in Tab.2) is less than that of brick-concrete structure, frame structure and shear wall structure, and less materials are used for the same mechanical performance[4]. For example, the dom-101 box structure produced in Yugoslavia uses 30~40% more steel than the traditional structure and 10~18% more material, but saves nearly 70% labor. Considering the high labor cost and cheap materials, the total cost is still 15~20% lower than the traditional structure, and the construction period can be shortened by 50%. Overall, it is economical[5].

| Tab. 2 Thickness of concrete wall |
|----------------------------------|
| **Thickness (mm)**  | External wall | Internal wall | Partition (240mm wide) | Beam | Column | Top plate | Bottom plate ribs |
|---------------------|--------------|---------------|------------------------|------|--------|-----------|------------------|
| Thickness           | 200 60 70 120 100 40 100 |

Since steel is considered to be a reusable material and cement has a relatively large carbon footprint, the pre-fabricated pre-finished volumetric modular building has the effect of reducing carbon emissions. In areas where clay bricks are used to build multi-storey houses, this technology can save a lot of land damage and air pollution caused by brick-burning, and at the same time avoid the release of CO2 solidified in the land[6].

2.3. Low carbonization of materials in non-stressed parts of pre-fabricated pre-finished volumetric construction

Optimizing building structural design to reduce modular concrete content techniques include:

1. The precast concrete modules are designed to slim down walls by applying high-grade concrete and adding steel or specifications.

2. A concrete module adds a box to its facade, adding a column and beam to the structure, allowing it to be replaced by a low-carbon or functional material. For example, in the nine-storey box house in Krasnodar of the Soviet Union, the exterior facade is rib, and the overall material of the modules is ceramic concrete [7].
(3) A tubular reinforced pre-fabricated pre-finished volumetric module is built to itself without having to create two short-sided concrete walls, both of which can be replaced by recycled, recyclable and reusable materials.

(4) The space shape of volumetric modules are usually simple, so modules can be used to cleverly enclose the space between the modules when large and diverse spaces are needed. After structural calculation, the volumetric modules are likely to be used as the support structure of the roof and wall of the large space, and the envelope structure of the space between the volumetric modules only needs to be built with light structure, which may save the material of the support structure.

It is known that each ton of cement produces about one ton of carbon dioxide. Currently, the world uses about 2.5 billion tons of cement every year, and the production of these cement accounts for more than 5% of the world's carbon dioxide emissions[8].

Take for example the zero carbon pre-fabricated pre-finished volumetric modular beachfront bath project with a foldable garden, as shown in Fig.1. The yellow section of the profile shows the prefabricated standardized overall whole modules for the men's and women's bath rooms, while the blue roof of the middle garden is created by the aluminum alloy frame and transparent polycarbonate panels that fold over the walls of the bath rooms on both sides. The red and orange part of the wall is not reinforced concrete part: the red part is replaced by polystyrene board, and the orange part is the opening of each shower to the garden. The grey grooves in the module bottom plate are also the part that can be hollow-out after structural calculation, which saves the concrete consumption and facilitates the layout of the water pipe system.

![Fig. 1 Zero carbon pre-fabricated pre-finished volumetric construction module beach bath with foldable garden.](image)

3. Carbon reduction path for the industrial production process of pre-fabricated pre-finished volumetric construction module

3.1. Integrated turning process of pre-fabricated pre-finished volumetric modular building

On a traditional construction field, the quality of structure connections, bonding composite, and installation is affected by climate, weather, and the technical level and responsibility of the construction team. Fieldwork conditions and inadequacy of machinery and equipment may affect standardized processes and quality.

The pre-fabricated pre-finished volumetric modular building technology system transfers the on-site construction to the automatic and specialized processing in the factory, and simplified the layered installation process of the steel structure envelope with the single-cast concrete. The main processing process of pre-fabricated pre-finished volumetric module is: Steel mesh automatic processing - space steel frame assembly - pipeline layout and embedded parts, etc - secure insulation board - add texture template - mechanical fixed die - reinforced skeleton into the steel mould - pouring concrete in hot die - vibro - side templates, steam heating plate and core mould cavity maintenance - automatic
demoulding - casting connection underside - decoration production line - equipment installation -
testing - packaging - finished product storage.

The integrated casting molding of building insulation layer, components, pipelines and module structure avoids the installation of scaffolding and supporting formwork first according to the process construction on site, and replaces a lot of manpower construction. The professional equipment and steel mold turning process of the factory ensure that high-quality module products can be obtained with simple operation. Thus solving the contradiction between the construction progress, energy saving and heat preservation, sturdy and durable, comprehensive cost performance of these four key issues between.

3.2. HVAC pipelines and their equipment integration and assembly modules
The HVAC pipeline with the same life span as the building is integrated into the pre-fabricated pre-finished volumetric modular building and other pipelines are arranged in pipe wells and ceiling. The connection boxes are set in the ceiling of the corridor, kitchen and toilet, with the repair port near the connection boxes. The integrated water, heating and electric pipelines are designed to be installed in an aluminum alloy frame, prefabricated by a branch plant or other workshop, and shipped to the assembly line of the main plant or the construction site for overall assembly. Air conditioning external machine and other equipment are also designed to the corresponding positions in the volumetric module according to the function and building appearance. The volumetric module pipelines and facilities have the advantages of factory automatic processing and dry installation with low cost, small error and material saving.

3.3. Assembled indoor and outdoor decoration and module integration and assembly
The decoration line of concrete modules includes ceiling, floor, kitchen module, toilet module and fixed furniture module. The decorative layer can also be integrated with the module at the time of production, for example by hitting the tile back against the concrete slab. A bedroom module decoration line in Krasnodar, Soviet Union, a total of 18 processes, taking about 2 hours and 35 minutes. The Swiss module builder produces an average of 40 modules day and night. The process flow of reinforced concrete module production in a prefab factory of an Italian company. One production line can produce 2 modules per class, and the whole factory has 6 production lines and 12 modules per class[6]. In the factory, the building process can be generalized, standardized, modular use of advanced equipment and professional process accurate processing, steel mold overall conversion process and decoration integration technology to ensure that the simple, automatic operation to obtain high-quality module products.

4. Carbon reduction path of pre-fabricated pre-finished volumetric modular building assembly and demolition construction process

4.1. Integrated assembly construction of pre-fabricated pre-finished volumetric modular building
The traditional concrete construction has many problem such as excessive construction process, too long construction period, and too much waste of materials and energy on construction site. Compared with pre-fabricated pre-finished volumetric modular concrete building construction, 2D prefabricated concrete structure construction has more connection nodes between field supporting forms, pouring walls and beams and columns in the site. Due to the concrete pouring work on site, the interior decoration could not be completed in the factory.

The pre-fabricated pre-finished volumetric modular building construction site simply involves stacking the volumetric modules together, fixing the connection members, and waterproofing and decorating the joints between the modules. The pre-fabricated pre-finished volumetric modular building construction avoids a large number of outside construction, improves the safety and accuracy of construction, saves half of the time, and reduces the impact of construction on the environment. Reduce the manpower and time required to construct the building while ensuring that the site is safe,
beneficial and has minimal impact on the surrounding living environment. Take the two residential buildings with an area of 7515.82m² in the northwest group of Daxing Zao Community as an example, each with 324 concrete volumetric modules, the main structure assembled only took 25 days, and has a total period of 6 months. If the concrete cast-in-place structure or prefabricated frame structure is used, the construction quota is more than 300 days[6]. Compared with traditional methods, the saving effect of building using the pre-fabricated pre-finished volumetric modular building system is shown in Tab.3 in Singapore[9].

| Total cost | Formwork cost | Scaffold cost | Structural human cost | Human cost | Pipeline human cost |
|------------|---------------|---------------|-----------------------|-----------|-------------------|
| Saving effect | -40% | -75% | -95% | -40% | -70% | -70% |

In addition, where there is no module factory, the basic processing equipment and molds can be moved to the construction site for production: it has been tried in the US made box concrete member near the construction site, after the concrete was enough strength, with a crane to lift table, around its vertical panel is connected, bolted, connecting the embedded parts, grouting, the hoisting position to design again, to use this method can be built up to 16 layer architecture, in Auckland built some 11 layer building in this way. It was said to save $100,000 compared with sliding mode and shorten construction by 4 months[6].

4.2. Green construction site and transportation equipment
The temporary office and living space on site is a movable reusable modular building based on metal spiral piles, scientifically equipped with building insulation and shading devices. Distributed photovoltaic power generation equipment, small wind turbines and solar collectors are installed on the roof of the building to meet the energy needs of the building. The construction road uses the construction waste crushed by the original building as the aggregate of the main raw material. Transportation and installation of equipment are powered by clean energy, and energy feedback technology is used to reuse the renewable energy.

4.3. Remove the pre-fabricated pre-finished volumetric module as a whole and reuse
Different from the destructive demolition of traditional buildings, the pre-fabricated pre-finished volumetric modules themselves can be used as recyclable parts. The demolition of the modular building only needs to cut off the connections, fittings and pipelines, and the indoor decoration of the module is basically not removed, which can be reused in other places. For new buildings where this module is used, the module as part is almost zero carbon. The cast-in-place concrete portion of the building can be crushed and reused as aggregate for the concrete material.

5. Carbon reduction path of pre-fabricated pre-finished volumetric modular building during operation stage

5.1. Modular green nearly zero energy consumption building technology
The enclosure structure plays a role in controlling the energy exchange between indoor and outdoor. It can integrate green building technologies and components such as heat preservation, lighting, natural ventilation and plant modules into the modules, and develop modules with green and low-carbon building functions. The wall panel, roof and bottom plate of the concrete integral pouring the pre-fabricated pre-finished volumetric module have almost no joint, and there will be no sealant aging phenomenon, and the insulation, thermal inertia, air tightness and water tightness are better than conventional buildings. Building carbon reduction design can be carried out according to the technical Standard for Nearly Zero Energy Consumption Buildings, which takes building energy conservation
environmental parameters, energy efficiency indicators, technical measures and evaluation as technical standards. For example, the zero carbon pre-fabricated pre-finished volumetric modular beach bath building’s envelope is the sandwich insulation structure of the module products, which can choose super light, thin air gel nano insulation thermal insulation material. Traditional sandwich insulation in the site construction has many processes and high cost, which is not as good as airtight and firmly durable as the integrated processing in factories and modules. In addition to the side windows and doors for natural ventilation, the side walls of the elevated roof above the garden are equipped with windows that serve as exhaust vents for atrio-style thermal ventilation. The bathroom entrance and hallway window serve as the entrance to fresh air. These Windows also ensure that the bath room does not need artificial lighting during the day. The shower center displaces a lot of water and is a waste of resources if it is not recycled. Therefore, each shower center module is equipped with water purification equipment with the functions of collection, filtration, purification and sterilization.

5.2. Passive solar building technology integration pre-fabricated pre-finished volumetric module
Heating energy consumption accounts for a large proportion of building energy consumption, solar energy as a sustainable clean energy if direct use is the most natural, effective, low-cost way, so passive solar energy technology is set in the model library in the form of modular building parts, including its energy-saving parameters and optional structures in different regions to be transferred and manufactured. The passive solar cover of the pre-fabricated pre-finished volumetric module can be a window, sun room or metal heat sink, and the heat storage surface can be concrete walls and floors with phase change material added. In winter, when the sun hits the room during the day, the heat is absorbed and stored, and released into the room at night. In summer, the principle of hot pressure ventilation can also be used to drive the cold air at night to cool the room, and the cold energy can be stored in the building structure to cool the room during the day. Solar heat collection cover can be set to automatically adjust the sun visor shading, adjusting the Angle of the winter sunlight into the room. Take the beach as an example, the bathing module during the period of receiving tourists needs to be installed with shading measures to cool down. LOGO plant walls are installed on the south facade, and solar vacuum tubes and photovoltaic panels are installed on the roof to shade the roof.

5.3. Renewable energy installations integration pre-fabricated pre-finished volumetric module and carbon-negative landscapes
The use of renewable energy is the main way to reduce the carbon emissions of buildings. Solar heat collection system can provide energy consumption for heating, namely domestic hot water. Photovoltaic power generation system can provide electricity for the building operation phase. For the beach shower center mentioned above, six groups of 58×1800×50 split solar vacuum tube heat collection system, transparent glass roof type 3000W photovoltaic power generation system and 500W small wind power generation system are arranged according to the roof size and energy demand. During the beach tourism off-season, the shower center is converted into a solar hot water sales center and a solar scenery complementary power farm. The benefits of photovoltaic film panels and glass top sets becoming a photovoltaic roof are that solar equipment saves the cost of brackets and backs, and the roof shares the glass cost of the outer surface with the photovoltaic panels.

Sewage filtration, disinfection and reuse equipment are installed in the shower module to reduce carbon emissions in the production and transportation of tap water, while extracting heat reuse from the wastewater. Zero carbon buildings collect temperature and other data through collection equipment, control equipment, and data analysis platform to realize intelligent control of comfort, exhaust, lighting, solar system and other on, turn off ineffective operation of equipment, reduce operating energy consumption, thus reducing carbon emissions. Several small tree flower bed modules are arranged in the garden between the two shower modules of the beach bath building and the waiting platform at the outdoor entrance, providing a view and some CO₂ absorption.
6. Conclusion
This paper proposes the carbon emission reduction path for the modular building technology system, including:

(1) Standardized, modularization and menu-based unit pre-fabricated pre-finished volumetric modular structure system and optimizing structure design.

(2) Volumetric modules integrated production, structure, insulation, decoration, pipeline, etc.

(3) Volumetric modules integral installation, low carbon transport and integral removal methods.

(4) zero energy consumption building envelope, renewable energy and pre-fabricated pre-finished volumetric module integration technology.

The assembly rate of pre-fabricated pre-finished volumetric modular buildings is greater than 80%, reduces the construction site waste by 80%, saves the site construction period by 80%, and the total cost of building construction is 20% less than the conventional construction method. The research and promotion of this technology will make up for the reduction of construction workers caused by the aging population, balance the increased greenhouse gas emissions caused by increased building number and increased comfort, and make safer and efficient use of renewable energy. The pre-fabricated pre-finished volumetric modular construction system is a preferred scheme for the transformation of the construction industry to high quality, industrialization and digitalization. The volumetric module will become one of the most popular prefabricated products in the international architectural blue ocean market.

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