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Generative Shelter: Sustainable Methods for Organizing Prefabricated Housing with Integrated Greenhouses

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Abstract: The problem of food supply during the creation of prefabricated settlements is particularly acute in areas affected by natural and man-made disasters. Bio-shelters with autonomous greenhouses are becoming a sustainable strategy for providing food to populations in areas remote from existing infrastructure. The article provides a systematic analysis of methods for integrating greenhouses into the structure of prefabricated housing. Current examples of various technologies for integrating green elements into the residential structural design are considered. Greenhouse integration methods, such as *attached*, *combined*, *accompanying*, *microcapsular* and *growing* are identified. Using student experimental projects with autonomous greenhouses as part of educational design, the principles of greenhouse integration are implemented.

1 INTRODUCTION

In conditions of social and geopolitical instability, architectural concepts with integrated technological components capable of producing goods autonomously are gaining popularity. The integration of all functions within a single residential structure ensures prolonged survival in a newly forming environment, isolated from key infrastructure elements: engineering networks, transport routes, food supply chains, and global connections.

The article focuses on innovative solutions and technologies dedicated to incorporating mobile greenhouses and portable gardens into the structure of rapidly deployable housing.

The growth of greenhouse inclusion technologies in residential and public buildings will ensure the transformation of the urban landscape in the image of eco-sustainable cities of the future.

2 MATERIALS AND METHODS

In this article, the term "*bio-shelter*" refers to an architectural object primarily used for residential purposes, the structure of which includes a biological component — a greenhouse. A related term is "*vegetarium*", which is a greenhouse attached to the exterior walls of a country house. Such an eco-sustainable house, when insulated with foamed polyethylene, is suitable for use in low temperatures down to -65°C (Shokodko et al., 2020).

Interest in bioclimatic projects is also confirmed by the world architecture exhibition themes. Coldefy & Associés's "Tropicalia" project elevates greenhouse architecture to the status of a self-sufficient bio-dome, capable of storing energy and servicing the 20,000 m² botanical garden and nearby facilities. This generally makes the greenhouse a starting point for the life of residential and public areas.

Greenhouses are increasingly being incorporated into public buildings, becoming their integral component. Within ALOT's "Framescape" restaurant project in Iceland visitors navigate a winding path through a vegetable garden before entering the main dining room. This increases visitors' awareness of the origins of the products and establishes a connection with nature and the landscape.

Latest projects like Heatherwick Studio's "Glasshouse" make these structures a flagship for the development of innovations in kinetic architecture. This 140 m^2 greenhouse is covered by ten glass petals

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that can be opened hydraulically in four minutes (Figure 1).

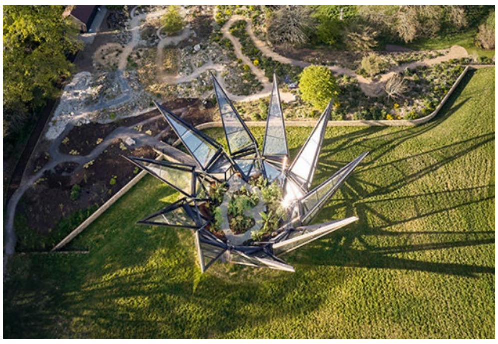

Figure 1: “Glasshouse” by Heatherwick Studio, 2022. Source: https://www.designboom.com/architecture/heatherwick-studio-glasshouse-kinectic-woolbeding-gardens-06-27-2022/

The development of bio-shelters is part of the global Building Integrated Agriculture initiative, which aims to grow food in diverse anthropogenic environments (D’Ostuni et al., 2022). A bio-shelter is an innovative facility capable of providing protected shelter and autonomously cultivating resources in conditions of social and geopolitical tension (involuntary migration, the effects of political conflicts, and other anthropogenic threats).

The integration of biocomponents into architectural structures is part of the spectrum of agroecology tasks and is carried out within the framework of progressive concepts of modular high-rise buildings (Saprykina, 2023). For example, the “Honeycomb” skyscraper presented within the Evolo Competition 2017 (authors: N. Badr, N. Maestro, H. Elahmar) implements high-altitude agriculture using hexagonal modules arranged into a vertical, futuristic structure (Kizilova, 2023).

The resource deficit can be compensated for by innovative plant growing methods implemented on the basis of architectural objects: aqua- and aeroponics, hydroponics, drip irrigation, bridge farming (Zhang et al., 2022).

The range of integrated greenhouse solutions for residential environments is currently expanding to reduce the carbon footprint of cities. As part of an experimental project, the roof of the Research Center ICTA-ICP UAB Barcelona was greened. The greenhouse, which received heat from the building during the cold season, demonstrated superior energy efficiency compared to a stand-alone greenhouse (Nadal et al., 2017).

Greenhouse maintenance within residential buildings is also becoming an important task. These operations can be carried out autonomously thanks to innovative technologies that combine robotics, IoT sensors, coordinators and apps that manage crop cultivation and collect soil and environmental data (Thomopoulos et al., 2021).

Thus, the development of approaches to the organization of autonomous greenhouses serving residential units is becoming an important and pressing task, requiring the accumulation of new architectural solutions.

3 GREENHOUSES WITHIN THE LIVING ENVIRONMENT

3.1 Types of greenhouse placement in the shelter structure

The nature of the integration of greenhouses into a bio-shelters can be achieved in several ways. Let us consider the following main approaches.

3.1.1 Attached Greenhouses

A private greenhouse can be incorporated into an architectural structure as an extension. The prefabricated housing and greenhouse project “ReGenVillage”, designed by Effekt Architects, is intended for implementation in Almere, the Netherlands (Ehrlich et al., 2021). The concept proposes a new sustainable model for living on a private plot, based on the regeneration of the built-up area and the reduction of the footprint of service components for the production of energy, food, and water storage (Figure 2).

Figure 2: “ReGenVillage” by Effekt Artchitects. Source: https://www.designboom.com/architecture/effekt-naturbyen-nature-village-venice-architecture-biennale-05-11-2021/

A similar principle is characteristic of the sustainable architecture of ecovillages. The average plot of land in Denmark is 1,400 m^2, while only 139

m^2 is used as living space. By converting the surrounding area into a greenhouse and a space for resource production, the impact on the natural landscape is reduced. The household grows crops using aeroponic and hydroponic methods, providing food for the entire household. The roof of the attached greenhouse is equipped with solar panels and a water reservoir. Excess stored energy is supplied to the community's shared grid, which powers electric vehicles.

Waste is involved in the variety of economic needs. Compost from agriculture is used to produce biogas and energy. Other waste support insect farms (species *Hermetia illucens*), which are capable of naturally decomposing biowaste and serve as a feed resource for the fish farm. Fish waste, converted into nitrites through biofilters, is used to support plant growth in an aquaponic farm. In this way, a closed production cycle is achieved within a single living cell. The house is suitable for cold regions, as it retains heat in the extension at low temperatures and prolongs the harvest season.

3.1.2 Combined Greenhouses

The greenhouse can be combined with a structural frame. Studio Precht architects designed a high-rise modular greenhouse, integrated into the basic cell of the building (D'Ostuni et al., 2025). It is expected that this type of housing will be used in cities to reduce the negative impact of product transportation on the environment. The modules can be used to form both individual dwellings and city skyscrapers.

The residential units are constructed from cross-laminated timber (CLT) panels on an A-frame. The module walls consist of three layers: an interior layer housing utility system, a middle layer containing insulation, and an outer layer with hydroponic greenhouses. The minimum 10.5 m^2 module is designed as a two-story unit with a combined kitchen and living room on the first floor and a bedroom on the second floor. With the high-rise configuration of the structure, buffer zones of greenhouses will be located at the junctions of apartments.

Naturvillan's "Atri" greenhouse house is also built on an A-frame and is equipped with its own autonomous heating, electricity, water supply and heat recovery systems (Figure 3). A ribbon of solar panels mounted on the roof provides energy for the house's internal systems (heating, hot water, and powering electrical appliances). Water is extracted from a private well developed on the construction site. Grey and waste water are purified during the growing process in the indoor greenhouse.

Figure 3: "Atri" greenhouse by Naturvillan. Source: https://www.designboom.com/architecture/naturvillan-a-frame-self-sufficient-off-grid-sweden-07-04-2022/

3.1.3 Accompanying greenhouses

A private greenhouse can act as a "companion" to a residential home, moving alongside it in various environments, including on water. The "Jellyfish Barge" project, developed by Studiomobile, is a timber-frame farm that can serve various communities by navigating waterways (Liebenberg, 2024).

The structure has an octagonal plan with an area of 80 m^2 and is placed on a movable buoyant base made of plastic tanks fixed to the frame (Figure 4). The device is capable of capturing condensate from the steam of contaminated water, undergoing a natural purification process. The roof is equipped with solar panels that power the pumps and fans. The floating greenhouse uses 70% less water for hydroponic cultivation than a traditional greenhouse.

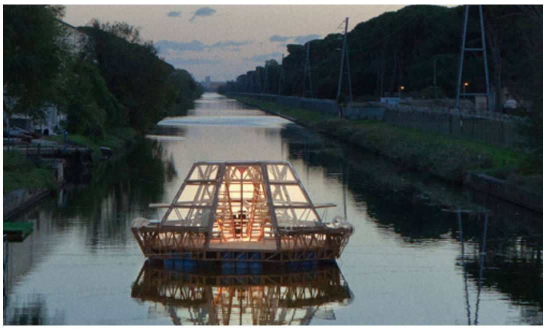

Figure 4: "Jellyfish Barge" greenhouse by Studiomobile. Source: https://www.designboom.com/architecture/studiomobile-jellyfish-barge-floating-greenhouse-11-19-2014/

A floating greenhouse can also be established in saltwater conditions, using the minerals contained in the seawater to grow crops (Lu et al., 2024). The soil for plant cultivation is built up on a 5-mm-thick fiber base using seawater agriculture method. This technology can save 90% of the water for production compared to traditional farming.

A similar technique is used in N-ARK's "Green Ocean" floating farm project. The greenhouse roof is conveniently shaped to collect rainwater, which is mixed with saltwater to fertilize the plants.

3.1.4 Microcapsular greenhouses

A greenhouse can be designed as a micro-structure integrated into a home, either as a small suspended or built-in structure. "Zero yen house", designed by Japanese artist and architect Kyohei Sakaguchi, is supposed to be built from recycled materials without the need for additional funds (Gillespie, J., 2021).

The houses are made from cardboard boxes, wood scraps, vinyl sheets, old telephone booths, and reed mesh. The "Zero Yen House" in Nagoya, which is a part of similar home series, was built on an abandoned playground slide. The dwelling is integrated with a portable hydroponic farm and a solar panel installed on the roof.

A mobile dwelling developed by People's Architecture Office creates individual, minimal living space within metropolis environment. The "Tricycle House" moves on a three-wheeled bicycle equipped with a movable platform. Individual sections of the translucent plastic shell were milled and glued together to form a single structure. Amenities include a sink, stove, bathtub, water tank, and furniture that can be transformed from a bed to a dining table or a bench.

Presented at the "Bee Breeders Microhome competition – 2019", the "Shifting Nests" project is designed to be installed in Vancouver's vacant, unused spaces as an alternative to expensive rental housing in the metropolis (Figure 5). The 25 m² frame structure is clad in metal sheets (in the heated area) and corrugated polycarbonate sheets (in the unheated area). The interior contains a living space, including a sitting area, a kitchen and a bathroom. The open area includes a hydroponic greenhouse, allowing residents to grow their own produce and use it in their garden.

Figure 5: "Shifting Nests" by BLA Design Group. Source: https://www.designboom.com/architecture/shifting-nests-bla-design-group-sutainable-prefab-micro-homes-09-04-2020/

3.1.5 Growing greenhouses

A greenhouse can be organized as a living shield based on the shell of a dwelling and develop autonomously.

For the "Tree House competition – 2020", Score Architects submitted "Cocoon" project, which is a suspended and floating parametric structure. Interior space serves as a shelter, while the outer shell acts as a living nest for local flora and fauna (Figure 6). The project implements a synergy between anthropogenic living space and elements of the natural environment. The parametric structure, created by combined spheres, has an internal wooden frame and an external skin made of an organic hemp canvas.

Figure 6: "Cocoon" by Score Architects. Source: https://www.designboom.com/architecture/score-architects-cocoon-treehouse-09-25-2020/

Shelters made from earthen materials excavated from the construction site were made during Frank Lloyd Wright School of Architecture's curriculum at the experimental ecopolis of Arcosanti, USA. Artist Jessica Martin built the shelter from compacted earth layers found in the region. The shelter's upper layers serve as fertile soil for seeds that can grow on the roof, thereby providing residents with their own self-sustaining vegetable garden.

4 GREENHOUSE INTEGRATION ON THE BASIS OF THE EDUCATIONAL PROJECTS

The principle of combining a private home and a self-sustaining greenhouse was implemented as part of student projects at the Moscow Architectural Institute (MARCHI). The project titled "Private Residential Home with Self-sustainable Green Market" was completed by second-year undergraduate student V. Tumanova. It features a prefabricated dwelling with individual greenhouse on a timber frame (Figure 7).

Figure 7: "Private Residential Home with Self-sustainable Green Market" by V. Tumanova. Advisors: Ermakov Yu.A., Kizilova S.A.

The living quarters are set on the second floor, while the entrance is located at ground level. Natural ventilation is provided by movable screens. During the cold season, the heated lower floor helps reduce heating costs for the living quarters above. The house can accommodate up to six people at a time and features a combined kitchen, dining, and living area, three bedrooms, four bathrooms, utility rooms, and technical space. This house can be used for homesteading or as a market venue.

The integration of a garden into a courtyard was implemented in the student project "Two-block house: Traditions and Contemporaneity" by N. Kovaleva (Figure 8). The private house is divided into two parts: traditional and modern. The private garden is integrated into the traditional part as an inner courtyard, designed in the style of a Japanese national dwelling.

Figure 8: "Two-block house: Traditions and Contemporaneity" by N. Kovaleva. Advisors: Kizilova S.A., Vdovin Yu.A.

In the mansion project "Circles on the Water" by A. Klyueva concentric layout forms separated living areas, vegetable gardens, and orchards within the overall composition (Figure 9). The house is supposed to be created using 3D printing additive technology.

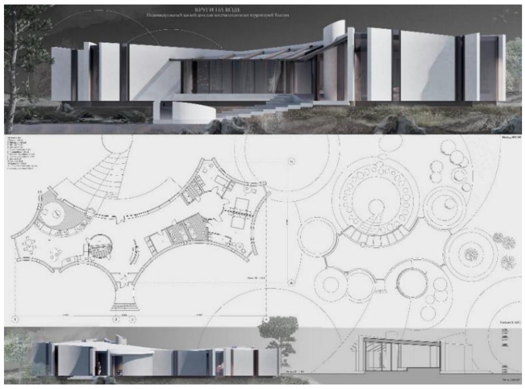

Figure 9: "Circles on the Water" by A. Klyueva Advisors: Kizilova S.A., Vdovin Yu.A.

5 CONCLUSIONS

The study identified the following current greenhouse integration methods:

- An *attached* greenhouse, which connects the greenhouse volume to one of the enclosing surfaces of the home;
- A *combined* greenhouse, the components of which are integrated into the supporting frame and modular elements of the home;
- An *accompanying* greenhouse, which is a separate structure transportable along transport routes and serving the main home;

- A *microcapsular* greenhouse, which represents a compact solution integrated into the shell of a micro-home.
- A *growing* greenhouse, which forms a living shield on the outer shell of the structure.

These principles were implemented during the student experimental design phase.

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