The Use of Roofs of Multi-Purpose Buildings for Allocation of Greenhouses: Specifics and Optimal Solutions

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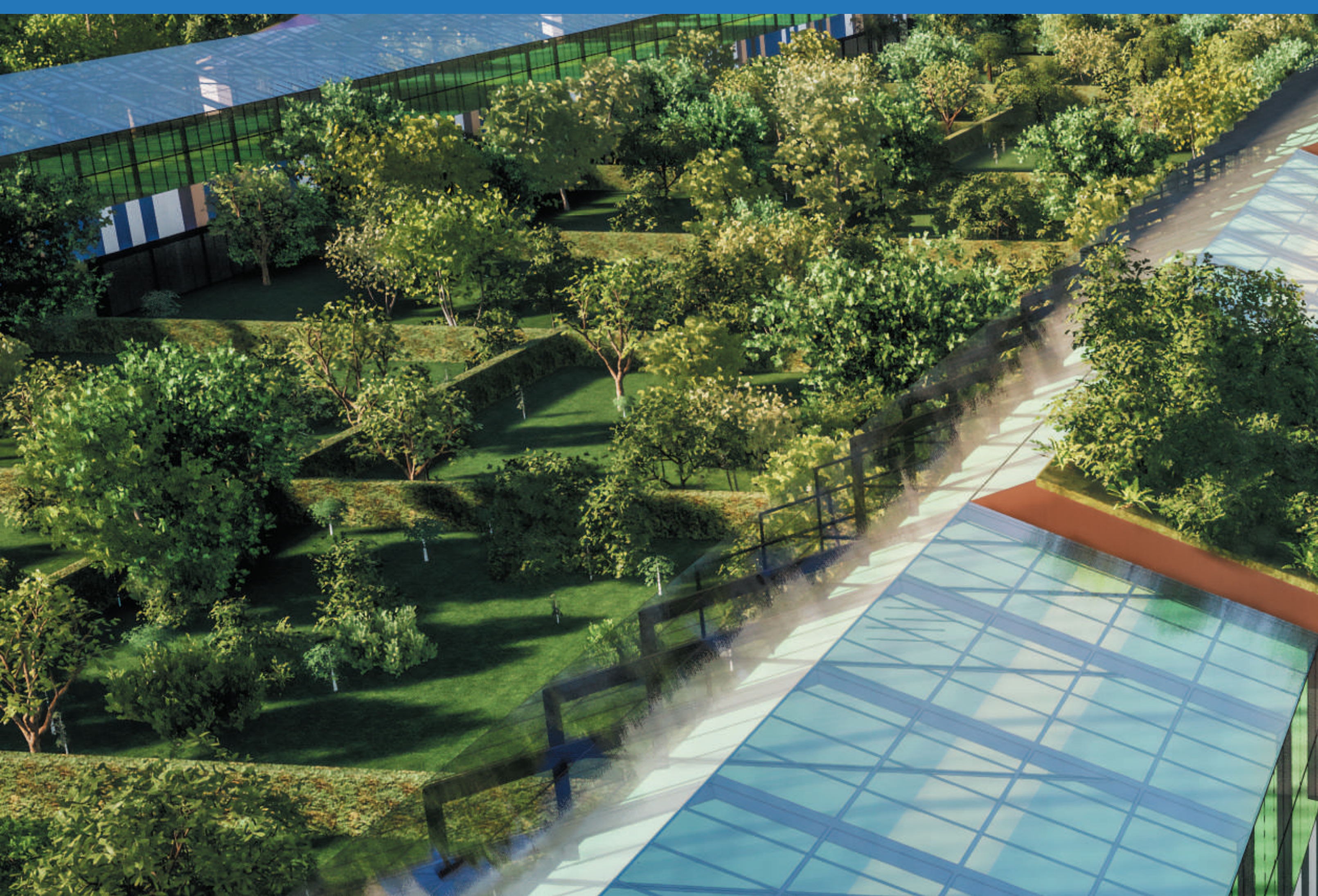
UDC 711.416-122



The issues of using the roofs of buildings for growing food products are considered. The experience of research and development in the field of creating technologies for the production of plant and animal food in an artificial habitat is summarized. The directions of searching for a new type of residential environment are indicated. Original approaches are proposed in the arrangement of the architectural and planning structure of a group of residential buildings made interlocked in an apartment complex called "horizontal skyscraper" (HS); its structural, engineering, technological and planning features are considered. The conditions affecting the possibility of using the roof when combining residential, industrial and auxiliary functional zones in the HS complex are described. The specifics of functioning and further development of such systems are indicated. The analysis of the possibilities of the HS as an element of a linear type of construction, aggregated with "second level" string-rail transport systems, is presented. The relevance of an integrated approach that can be applied, including the design of cosmic settlements "EcoCosmoHouse" (ECH) and their terrestrial analogues "EcoCosmoHouse on Planet Earth" (ECH-Earth), is noted.

Keywords: *city farming, EcoCosmoHouse (ECH), greenhouses on the roof, "horizontal skyscraper", linear type of accommodation, recycling, residential cluster, uCity, Unitsky String Technologies (uST), vertical greenhouses, waste-free technologies.*

Introduction

According to the Science Daily journal, on May 23, 2007, a demographic revolution took place in the history of the Earth: the urban population of the planet surpassed the rural one. The journal refers to the studies of scientists from the University of North Carolina and the University of Georgia. A study conducted jointly with UN experts showed that it was on the day when the share of urban residents reached 51.3 % of the total Earth's population. Currently, due to the disproportionate distribution of world wealth, rural areas often have a lower standard of living and at the same time receive urban waste – polluted air, water and soil [1]. It should be noted that at the end of 2021 the urban population was 54 % against 46 % of the rural one [2]. The recorded demographic shift indicates a negative trend.

The current situation requires the creation of effective accommodation systems (settlements of a new type) – linear cities (uCities) built on the basis of uST transport and infrastructure solutions (Unitsky String Technologies). The uCities reduce the dependence of households on oversaturated urban life and open up new ways of urban and rural development, which will allow to sustainably distribute the density of people over the entire surface of the planet and ease up the burden of municipal and national governments experiencing serious demographic pressure from overpopulated areas. Such autonomous accommodation systems will become the basis for building residential clusters of the Equatorial Linear City (ELC) as a ground-based structural element of the uSpace non-rocket near space exploration program and transferring the harmful component of the Earth's industry to the equatorial orbit.

The new type of settlements is based on the concept of autonomous existence and provide infrastructural, demographic and food security due to innovative high-tech food production in an urban environment.

Experience in Using Innovative Food Production Technologies

The idea of innovative food production is embodied in the use of potential urban reserves (roofing space of buildings and structures) and the application of a new way of farming (city farming) [3]. To test this idea in the largest megacities of the world, there are peculiar landfills equipped on specially allocated scarce spatial reserves. Greenhouses are located on the roofs of multi-purpose buildings and produce plant food products in a close proximity to the consumer [4].

The 1,900 m^2 greenhouse on the roof of the Brooklyn Whole Foods Market (Figure 1) in New York, USA, arranged by Gotham Greens company, produces annually more than 45 tons of fresh greens, and also protects the roof from overheating in summer and cooling in winter. The green-house operates using Aquaponics technology and produces food products with the use of highly efficient engineering equipment. LED lighting, improved glazing, thermal curtains, passive ventilation, solar panels can significantly save electrical and thermal energy.

The Urbs in Horto city farm (Figure 2) in the Pullman district of Chicago, USA, is located on the roof of the building of the Method company, which produces soap. The greenhouse supplies a large area of the city with products obtained without using any chemicals. The innovative greenhouse is located in the peripheral zone of the megacity and at the same time is a leisure center and a place of employment for the population living within walking distance, which is considered one of the conditions for a comfortable urban environment. Aquaponics technology used in cultivation of green products on this farm is based on the processes of plant growth and development under computer

Figure 1 – Greenhouse on the roof of the Whole Foods Market in Brooklyn, New York, USA [4]

control and demonstrates high quality products, ensuring the absence of herbicides, pesticides and antibiotics. This greenhouse with the area of 16,000 m^2 (1.6 ha) is equivalent in yield to 40.5 ha of land.

The farm project in Colomb, near Paris, France, will contribute to the emergence of a real agricultural city. Hydroponic greenhouses along the A86 motorway outside the French capital, becoming part of the new Magellan residential area, will provide its residents with fresh products all year round. The concept of a vertical greenhouse (Figure 3) was created by the Parisian architectural studio Ilimelgo. The multi-storey greenhouse combines traditional gardening and innovative technologies [5].

Specifics of Functioning and Development of Plant Food Production in Vertical Farms and Greenhouses on Roofs

It is customary presumed to call a greenhouse with a multilevel placement a vertical farm. If the requirements for the microclimate are met, it can be located in any premise: in a warehouse, on the territory of an old factory, on the roof of a building, in a basement. It is becoming popular to set up vertical mini-farms in residential premises, as well as to grow microgreens at home. Examples of simple hydroponic systems for home use by the Russian manufacturer "Wealth of Health" are shown in Figures 4, 5.

Figure 2 – Greenhouse on the roof of the Method company building in Chicago, USA [4]

Figure 3 – Vertical greenhouse concept designed by Ilimelgo studio, France [5]

Figure 4 – Hydroponic installation for home use

Figure 5 – Four-module microgreens germinator for home use

The main differences between vertical agricultural production and traditional greenhouse farms are multi-tiered arrangement and cultivation of green spaces using the controlled-environment agriculture (CEA), which allows harvesting all year round and significantly saving resources: light, water, electricity (Figures 6, 7). The term and idea belong to D. Despommier [6, 7]. He has calculated that 30 % of all the food produced deteriorates during transportation and storage, while farming in vertical farms in cities significantly reduces the logistics component and the time of delivering green products to the consumer's table.

Figure 6 – Application of CEA method in vertical farms [8]

The iFarm company is currently operating in the Russian Federation market. It is not only engaged in the construction of vertical farms, but also produces environmentally friendly products itself [8]: various types of salads, spicy herbs, vegetables, berries (Figure 8). On a vertical farm in Tomsk, the company uses nutritious phyto-solutions, selected methods of biosecurity of salads and vegetables from diseases. It also adjusts watering and the use of phyto-light.

The iFarm company has calculated the parameters of the technology (Table 1), which show the efficiency of building vertical farm modules produced by it in a wide range of premises.

Singapore is home to the world's first commercial vertical farm Sky Greens, where greens and vegetables are grown in 38-tier containers in which plants receive sufficient water, sunlight and air and yield 10 times higher than the results in the open ground.

In the United Arab Emirates, there is a vertical farm Badia Farms. The installation occupies 790 m^2 and produces 18 types of leafy vegetables, including arugula, mustard and mint, without the use of chemicals and pesticides.

The Infarm company owns 50 vertical farms in Berlin, Germany, where it grows 200 varieties of vegetables, fruits, herbs, greens and mushrooms. Cloud technologies and big data analysis are actively used in farm management, helping to adapt the level of illumination, temperature, pH and nutrient composition individually for each plant variety [8].

Figure 7 – Farming with CEA method [8]

Figure 8 – Strawberry cultivation in vertical farms of the iFarm company, Russian Federation [8]

Table 1 – Technological parameters of the iFarm company [8]

Parameter	Value			
Premise area, m^2	20	50	200	500
Growing area, m^2	47	117	478	1,000
Ceilings height, m/quantity of tiers in the module	3/7	4.5/9	4.5/9	5/9
Total number of modules (for seedlings and cultivation), pcs	4	10	41	115
Required power consumption (peak), kW	7	19	77	220
Harvest of greens (average value), kg/month	130	300	1,200	2,500

Development of Eco-Oriented (Biospheric) Technologies on the Roofs of Buildings

The movement of modern civilization towards harmonious relations with the environment and careful attitude to resources is becoming an urgent necessity. Increasingly, the attention of researchers and practitioners is attracted by the ideas of settlements of a new type – linear accommodation along transport corridors [9].

The uST transport and infrastructure complexes, which are being worked on under the supervision of engineer A. Unitsky, according to the EcoSpace program [10], make up a system of transport channels – the uNet communication and infrastructure network. The uCities and ELC, built using eco-oriented (biospheric) technologies, will appear on the basis of uST solutions. The planning unit of the new type of settlements will be a residential cluster consisting of "horizontal skyscrapers" (HSs) – interlocked into single-family low-rise buildings with a set of engineering systems that provide residents with everything necessary for life, including organic food, drinking water from artesian wells, electrical and thermal energy, as well as a full biospheric cycle of household recycling waste.

Urban agriculture, arranged in residential clusters, will improve the economy and ecology of cities, preserve the ecological environment, improve architecture and supply the population with fresh, environmentally friendly food. It is necessary to highlight some specific areas in the development of green technologies on the roofs of buildings:

- combining vertical greenhouses with commercial, office or residential structures, which will allow using heat and carbon dioxide that are present in air flows discharged into the atmosphere through exhaust ventilation, and redirecting them to greenhouses, saving energy resources spent on heating and obtaining carbon dioxide for plant fertilization;
- return of urban waste, including sewage, as secondary resources (recycling) into the chain of production and consumption, i.e., the waste will be processed into products, materials or substances regardless of whether they serve their original or any other purposes. A specific type of recycling is the processing of organic waste for composting [11];
- transition to the concept of modularity and compliance with the zoning requirements of technological premises. At the same time, it is supposed to create relatively isolated spaces (for example, plantlet, seedlings and vegetable sections), which will allow dividing the greenhouse area into automated regulated zones [12];
- formation of an automated control system to ensure the interaction of operational personnel with lower-level systems, implementation of dispatching control of processes and receipt of operational data from sensors in the systems of drip irrigation, microclimate monitoring, window ventilation, shading, carbon dioxide fertilization, additional illumination, as well as heating, air recirculation and automation of microclimate mode [12];
- application of multi-tiered narrow-cell arrangement and humusoponics, which uses liquid biohumus as plant nutrition, rather than chemical mineral substances, and allows for organic plant growing.

Organic products for cluster residents (people and animals) are planned to be grown in greenhouses located on the roofs of HSs in vertical farms. A solution with nutrients contained in soil humus – liquid biohumus – will be supplied to the root system of plants. This technology is natural in contrast to the traditional nature-like hydroponics based on chemical mineral compositions. After all, plants evolutionarily feed on substances that are formed due to the transformation of insoluble organic and mineral compounds into soluble salts of humic acids by a community of aerobic and anaerobic soil microorganisms that initially live in any naturally fertile soil.

Therefore, liquid biohumus should contain not only nutrients, but also communities of thousands of species of agronomically valuable soil microorganisms, and in greater quantities than, for example, they are contained in rich chernozem (about a trillion microorganisms per liter of humus). By analogy with hydroponics, this system is called "humusoponics". In the agricultural farms of uCities, just humusoponics will be used – when plants feed on liquid humus, where insoluble salts of humic acids have already been converted into a dissolved substance. Such experiments are successfully carried out in the Unitsky's Farm Enterprise, Maryina Gorka, Belarus.

In order to test innovative farming technologies in settlements of a new type, a large-scale project has been conceived on the basis of the Unitsky's Farm Enterprise – construction of a multifunctional building (Figures 9–14), in which various blocks will be combined, including residential, auxiliary, technical, as well as premises for growing and processing green food. The purpose of the experiment is to study and approve the advantages of such a combination.

At this facility, it is planned to install and test innovative technologies for heating, ventilation and air conditioning (HVAC); wastewater treatment and reuse; obtaining and using humus from organic waste and sludge accumulations of wastewater.

At Unitsky String Technologies Inc., Minsk, Belarus, research has been conducted and positive practical results have been achieved in testing certain technologies that are planned to be used in this multifunctional building: growing of tropical plants on lightweight soil [13], production of edible and medicinal mushrooms [14], production of natural phytoncide-containing extracts, liquid soap [15], processing of organic waste using vermicomposting and growing with the use of the resulting substrate of plant products (vegetables, green crops, microgreens) [16]. Using modern technologies, medicinal herbs are cultivated on the territory of the Unitsky's Farm Enterprise on an area of about 1,000 m^2 [17], and they also breed quails.

In the projected greenhouse, various pipeline systems are separated, transporting the following:

1) aqueous solutions of liquid vermicompost (adjustment of concentration of substances is possible);

2) rain water from storage tanks;

3) secondary water from domestic wastewater treatment tanks;

4) drinking water;

5) carbon dioxide gas for plant nutrition extracted from the fume emissions of a heat source.

Systems 1–3 can be combined with each other in a drip irrigation complex. All engineering networks are arranged in special zones that transit through a multifunctional building, executed in the HS ideology.

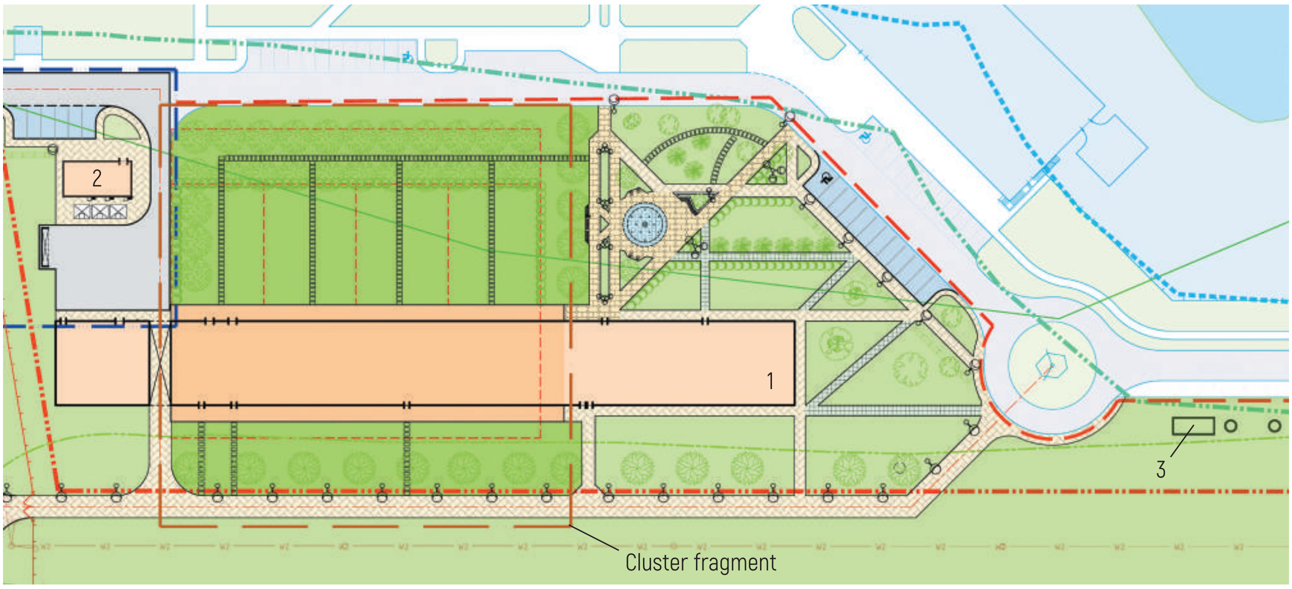


Figure 9 – Layout of a multifunctional building on the territory of the Unitsky's Farm Enterprise (variant):
1 – multifunctional building; 2 – boiler room; 3 – wastewater treatment unit

Figure 10 – General view of a multifunctional building
on the territory of the Unitsky's Farm Enterprise (variant)

Figure 11 – Structural diagram of a multifunctional building
made of prefabricated elements (fragment, variant)

Figure 12 – General view of the second floor
of a multifunctional building (greenhouse, variant)

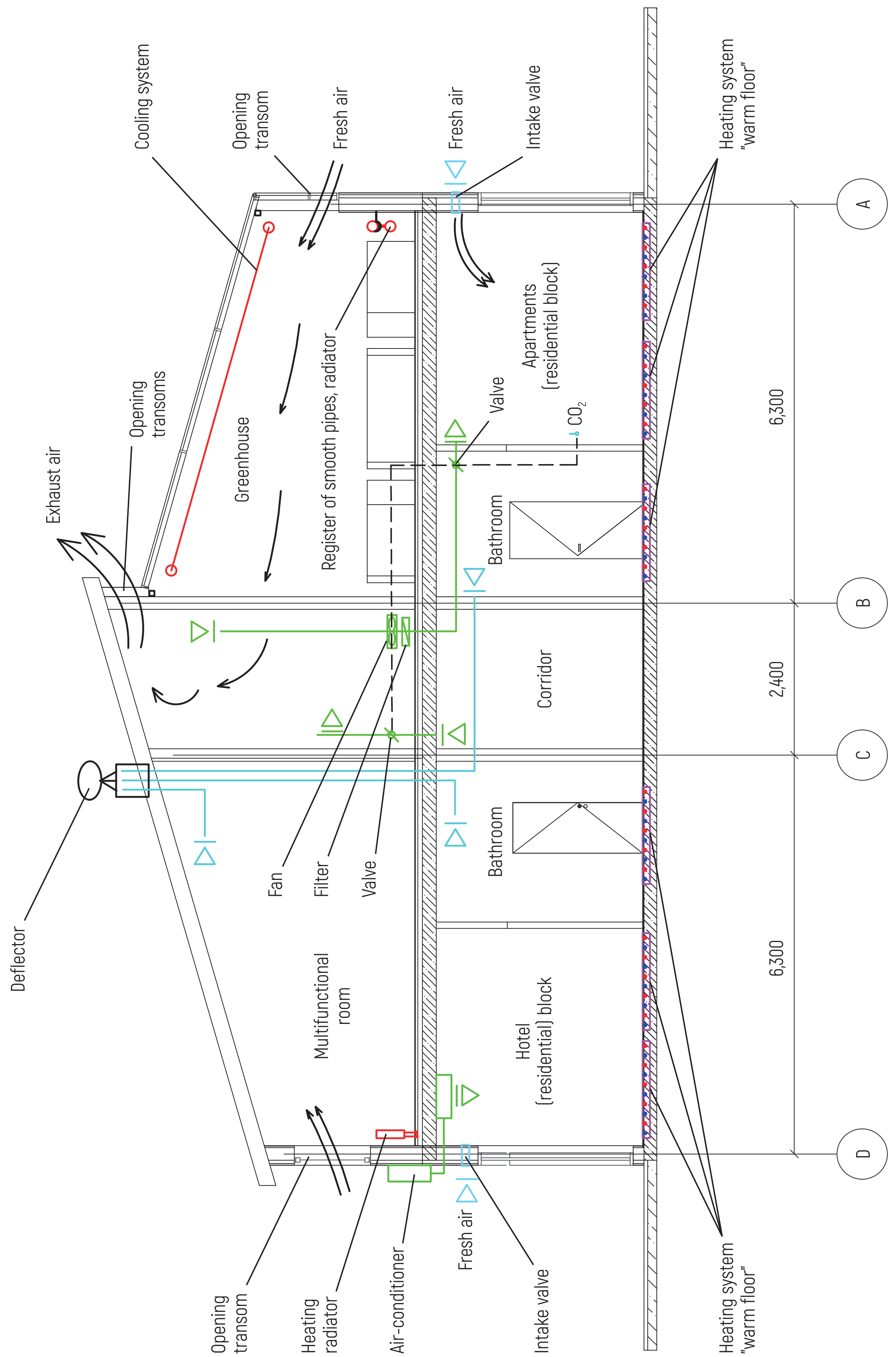


Figure 13 – Diagram of HVAC systems of a multifunctional building (variant)

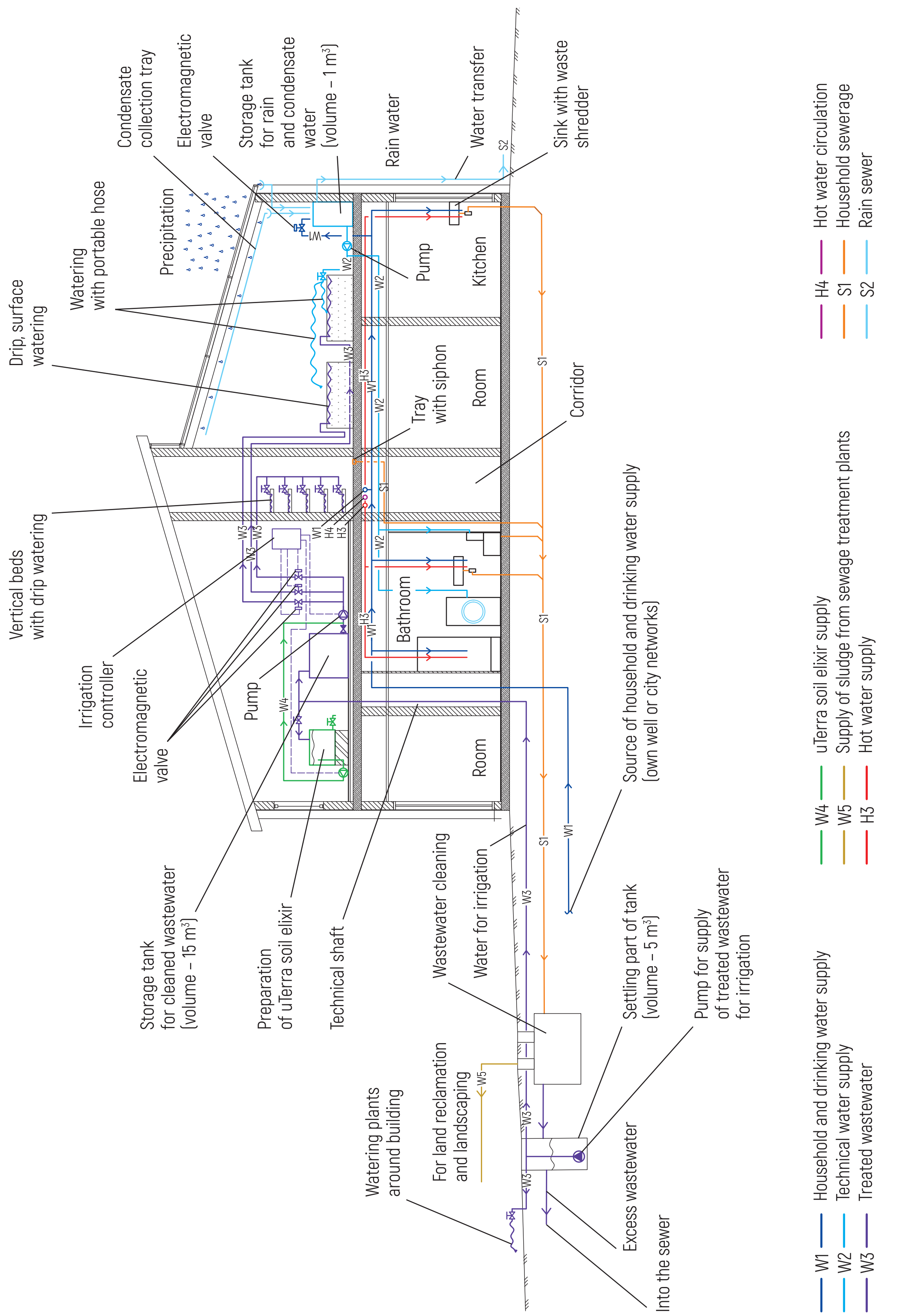


Figure 14 – Diagram of water reuse in a multifunctional building (variant)

Specifics and Conditions for Functioning of the Premises Located on the Second Floor of a "Horizontal Skyscraper"

The second floor of a HS in the residential cluster of the uCity will be rented by a farmer, and the residents of the house, as members of the condominium, will become participants in the process, receiving their part of the income from grown organic products. A year-round working farm will be able to produce enough food products on the roof of the HS to meet the needs of every family living in the house.

The rationally designed layout of the second floor is adapted for the functioning of a greenhouse. The entrance to the roof is arranged from the HS sidewalls. In the center of the building there is a through corridor with a narrow-gauge line for an automated cargo trolley transporting pallets with crops, humus, agricultural waste and auxiliary materials to cargo elevators arranged at the sides of the house.

The space of the second floor of the HS is divided into technological sections and blocks:

- a greenhouse for growing agricultural crops, medicinal herbs, decorative plants, which is a single premise oriented to the south side, covered with a glazed roof to ensure maximum light transmission;
- a room for growing microgreens in vertical farms;
- premises for microclonal propagation of plants (*in vitro*), which is based on the unique property of the plant somatic cell – totipotency, i.e., the ability of cells to implement the potential of the whole plant;
- a site for growing mushrooms (oyster mushrooms, etc.), which are a valuable dietary product that has a low-calorie content (38–41 kcal) and contains many substances necessary for the human body. Oyster mushroom is unpretentious to fluctuations in temperature, humidity and light levels, easy to care for, and is characterized by rapid germination [18];
- an area for breeding quails and other small animals to provide residents with dietary products (eggs, meat);
- a site for the production of biohumus and zoohumus. Biohumus is a biologically active, environmentally friendly and natural organic fertilizer, which is created as a result of processing organic residues in the soil by red California worms. Zoohumus is a product of the vital activity of fly larvae; it is a loose, finely granulated mass from gray to brown in color, having a faint smell of ammonia. Zoohumus is used as an organic fertilizer for all types of crops, in forestry and floriculture, as well as for the restoration of polluted soils. To obtain liquid vermicompost, it is proposed to use bio- and zoohumus together, and, if necessary, mineral components to regulate the content of certain elements. The mixture of biohumus, zoohumus and mineral components is diluted with water in a ratio of 1:10, then it is dispersed in a cavitation unit to a stable emulsion state. This suspension can be filtered and/or centrifuged. Figure 15 shows the general diagram of processing solid food waste to obtain plant products;
- public premises;
- utility area;
- dressing rooms, bathrooms, utility rooms.

In vertical farms, which are a complex of modules, plants are cultivated in conditions of protected soil and controlled environmental parameters. Mainly leaf and salad crops are grown, as well as microgreens, using such technologies.

Various types of microgreens have significant nutritional value not only for humans, but also for animals. Obtained on humusoponics, it is a natural organic food rich in easily digestible nutrients and vitamins. There are no chemical fertilizers and chemical means of protection (pesticides, herbicides, etc.) in this cultivation technology. Humusoponic feed from wheat seedlings (i.e., grown using humusoponics technology) as a green fodder additive or individual feed is energy-intensive and has a high content of proteins and fats, vitamins and other important micronutrients. It is fundamentally different from other ones, since the animal eats not only the aboveground part, but also the remains of seeds with starch, the root part rich in sugars and proteins.

Regardless of the time of year and climatic conditions (drought, heavy rains, heat, frost, etc.), humusoponic installations can provide both animals and people with fresh green food, which is especially important for vitamin deficiency in winter.

In addition to vertical farms, it is planned to arrange high round-shaped beds in the greenhouse on the second floor of the HS – cheap and easy to maintain, with a diameter of 1.91 m (perimeter of 6 m). They are easy to disassemble and relocate, service from all sides; each bed can be planted with its own culture.

The choice of plants for cultivation in the HS takes into account the food preferences of people and the peculiarities of the country's location (regional consumption traditions, seasonality of local production, price fluctuations, maintaining a healthy lifestyle, etc.).

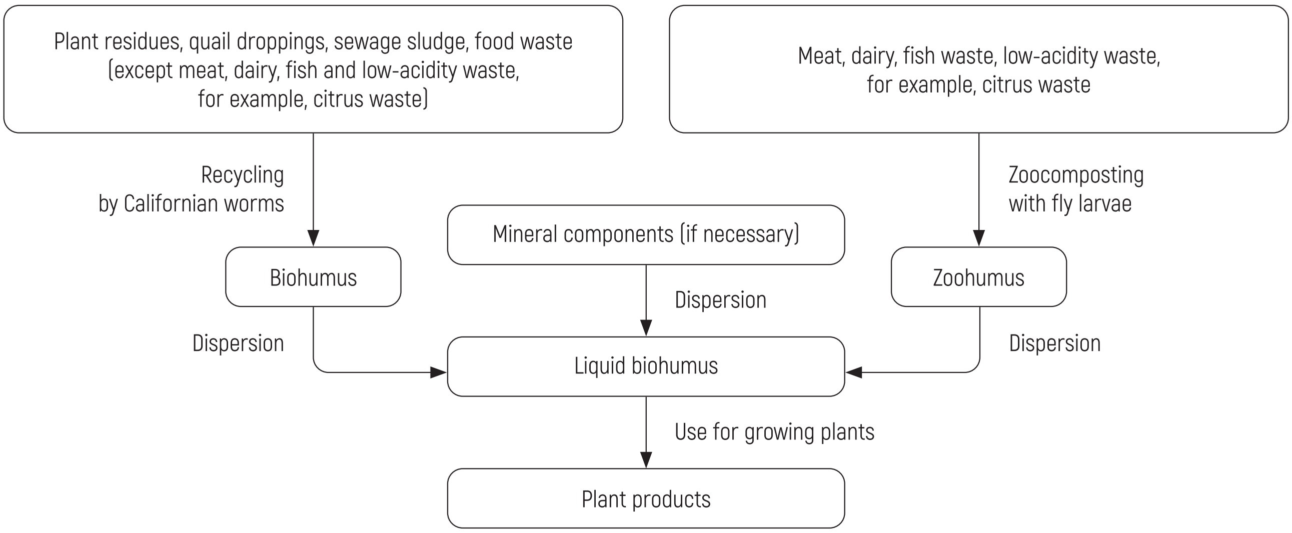


Figure 15 – Diagram of processing solid food waste to obtain plant products

The most optimal for the majority of plants valuable from a nutritional and/or medicinal point of view is a subtropical climate, therefore, the atmospheric conditions of the greenhouse are close to it. The entire space for growing crops on the roof of the HS is one climatic zone, the features of which are suitable for all plants selected taking into account the established climatic requirements.

To adjust the temperature and humidity in certain areas of the greenhouse, it is proposed to use mechanisms for local control of these parameters: fans, IR heaters, LED lamps, additional irrigation systems.

Climatic and technological conditions for growing crops in the HS are planned to be observed within the following limits:

- air temperature: 20–28 °C during the day, 16–25 °C at night;
- irrigation water temperature: 15–25 °C;
- humidity: 60–80 % (adjustable);
- type of lighting lamps: LED lamps with a spectrum of 380–780 nm;
- natural lighting and additional illumination: 10,000 lux;
- daylight period: 12–16 h;
- air exchange rate: 4–90 m^3/h per 1 m^2 (adjustable);
- CO_2 content in the air: 350–1,000 ppm (0.03–0.1 %) during daylight hours;
- installation in industrial greenhouses of an appropriate number of axial fans with a capacity of 0.25 kW each.

The irrigation system is planned to be automated: the volume and schedule of drip root irrigation of plants with purified wastewater of certain features are programmed (Table 2).

Table 2 – Requirements to wastewater for irrigation of plants

Indicator	Value
1	2
In accordance with the resolution of the Ministry of natural resources and environmental protection of the Republic of Belarus No. 16 dated May 26, 2017 "On some issues on regulation of discharges of chemical and other substances in wastewater"	
Biochemical oxygen consumption, mg/l, max	25
Chemical oxygen consumption, mg/l, max	125
Suspended solids, mg/l	30

End of Table 2

1	2
In accordance with GOST 17.4.3.05-86 "Nature protection. Soil. Requirements to wastewater and its precipitation for irrigation and fertilization" and the applied technology of cultivation of plant products, GOST 33045-2014 "Water. Methods for the determination of nitrogen-containing substances"	
Size of solid particles, µm, max	50
Total nitrogen, mg/l, max	31
Total phosphorus, mg/l, max	30
Total potassium, mg/l, max	58
pH, units	6–8
Microelements, heavy metals, pollutants	Taking into account their concentration in the soil and norms for cultivated crops
Unpleasant odors, on a five-point scale	Max 3
In accordance with Sanitary Regulations and Norms 2.1.7.573-96 "2.1.7. Soil, cleaning of populated areas, household and industrial waste, sanitary protection of soil. Hygienic requirements to the use of wastewater and its sediments for irrigation and fertilization"	
The number of LPC (lactose-positive *E. coli*), the permissible content of CFU per 1 l, max	10^4
Pathogenic microorganisms (according to epidemiological indicators), quantity per 1 l	None
Viable geohelminth eggs (ascarids, whipworms, hookworms), content in 1 l	None
Viable biohelminth eggs (teniid oncospheres, fasciol eggs), content in 1 l	None
Viable intestinal pathogenic protozoan cysts (giardia, balantidium cysts, cryptosporidium oocysts), content in 1 l	None

The amount of carbon dioxide absorbed by plants varies during the day and depends on the intensity of illumination and the quality of light (spectral composition of the luminous flux). The greatest need for CO_2 occurs in the morning and afternoon, when the photosynthesis process reaches peak values. If the needs of plants are not met and the concentration of carbon dioxide is increased at night, the growth and fruit formation processes slow down due to the suppression of plant respiration.

There are several types of carbon dioxide supply to plants: root feeding, at the point of growth, in the assimilating mass of the plant. Since carbon dioxide is twice as heavy as air and tends to accumulate at the bottom of the greenhouse, it is advisable to introduce CO_2 at the highest point – at the point of growth (with closed transoms).

To date, the most efficient and environmentally friendly equipment is considered to be the one that supplies to greenhouses not smoke, but carbon dioxide purified from impurities. This method requires a network of gas pipelines for distributing CO_2 to greenhouses and an automated gas supply control system. In addition, a storage tank for liquid carbon dioxide, a gasifier, a heater and other equipment are needed.

Inside the greenhouse, the gas is distributed by contours, i.e., the concentration of CO_2 in various parts of the structure is maintained at the same level. Independent gas supply to the greenhouse circuits is controlled with sensors, which in turn, on command from the controller, adjust the valve attached to this circuit [19].

Conclusions and Future Work

The use of roofs of buildings for growing food products is of paramount importance for the creation of a new type of residential development. Their principles of construction can be used not only in uCities, ELC, EcoCosmoHouse on Planet Earth (ECH-Earth), but also on space orbits in EcoCosmoHouses (ECHs). Technologies for obtaining plant and animal food in a controlled environment open up a fundamentally different level of production, distribution and consumption of natural goods and ensure the food security for the population of any country.

A new type of residential environment is based on combining many functions into a common architectural and planning structure, where groups of residential buildings interlocked into an apartment complex called a "horizontal skyscraper" make up a single structural, engineering, technological and planning organism. Such ecohouses during construction will not take away the land from the Earth's biosphere – from under the foundation of a building, even if it is desert sand, it will be raised to the roof, enriched to the fertility of rich chernozem with humus made from local organic waste, and will be able to feed a family living in the house with full-fledged organic food practically without involving additional external biospheric resources.

The fulfillment of the conditions described in the presented article makes the use of HSs roofs real and allows to combine residential, industrial and auxiliary functions into one harmonious whole. Being innovative, this way of creating a new type of living environment will become the basis for further developments. These features of the HSs functioning will determine the development of such systems as a key element of residential development of uCities and ELC settlements based on uST transport and infrastructure technologies.

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