Envisioning Urban Farming for Food Security during the Climate Change Era. Vertical Farm within Highly Urbanized Areas

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Abstract. Global climate change constitutes a serious threat to global security including food production in the following decades. This paper is focused on a new possibility and advisability of creating a systemic solution to resolve the problem of food security in highly-urbanized areas. The first part of the paper deals with historical development of vertical farms ideas and defines the main environmental and spatial constraints also it indicates that vertical farms are going to be part of the future horticultural production. The second part presents results of the research program undertaken at West Pomeranian University of Technology in Szczecin by authors. The program goes on to attempt to solve the problem through architectural design. This study highlights an integrating large-scale horticultural production directly into the cities, where the most of the food consumption takes place. In conclusions emphasizes, that the design will force architects, engineers and urban planners to completely revise and redefine contemporary design process and understanding of the idea-fix of sustainable design. To successfully migrate food production from extensive rural areas to dense environment of city centers, a new holistic approach, integrating knowledge and advances of multiple fields of science, have to develop.

1. Introduction

Global climate change has already had observable effects on the environment. Adaptation is a key factor that will shape the future severity of climate change impacts on food production. This adaptation will require substantial investments by farmers, governments, scientists, and development organizations [1]. In addition, the anticipated population growth by 2050, with an expected 70% of it living in the cities, forces a profound revision of recent efforts on food security and the means to accomplish it. [2]. Environmental and spatial constrains within highly urbanized areas indicate that vertical farms are going to be an important part of the future horticultural production. Although the food security problem is far more complex than solely undernourishment or even malnutrition. Understanding the interrelation scientists are developing sensitive agro-ecosystems and architects are envisioning new kinds of spatial structures for them.

The presented study is an application of the experimental approach to architectural and urban design in recently re-opened discussion on possibility and advisability of creating a systemic solution to resolve the problem of food security in highly-urbanized areas. It is a research for new solutions through implementation of advanced technologies and materials of the tomorrow [3].

2. Vertical Farms - past and present

The concept of incorporating rural landscapes into the city had been an idée fixe of architecture and urban planning throughout the entire 20th century. The evolution of city's paradigm in the early 1900s, especially in the United States, where buildings were growing higher and higher, gave free rein to then visionaries imagination. In the 1909, while Europe was yet at the Ebenezer Howard’s garden city movement stage, A. B. Walker daydreamed of probably the earliest fusion of skyscraper and farmland in his cartoon for ‘Life’ Magazine [4]. Published, as an advertisement for real-estate company was an idyllic vision of independent, vertically stacked ‘platforms' of homes set amid a countryside landscape (Figure 1a). In 1978 Walker’s cartoon became a subject of Rem Koolhaas’ considerations in his seminal book, “Delirious New York”[5]. He perceived it as a “theorem: the Skyscraper as utopian device for the production of unlimited numbers of virgin sites on a single metropolitan location”, [6]. This, then futuristic, housing structure may be nowadays, a widely recognizable reference to Walker’s vision and its interpretation by Koolhaas, is visible in numerous works of Paris-based architect Vincent Callebaut (Figure1b). His design for New York City "Dragonfly High-Rise Farm" (2009) shows a gigantic collection of farms, orchards, apartments and living places in one 132 floors epic building - practically a city within a city. The building will utilise captured rainwater, wind and sunlight in order to power itself [7].

Urban farming or urban agriculture and urban gardening is the practice of cultivating, processing, and distributing food in or around a village, town, or city [8]. Vertical farm, as the name suggests, refers to cultivating crops in multi-story greenhouses. These vertical farms are fitted with modern technology and enable crops to be grown within urban areas.

The real origins of vertical farming however, should be linked with development of hydroponic cultivation techniques and the Bengal System. A tower hydroponics unit in Armenia in J. Sholto Douglas’s book is probably the first such structure that ever registered. The publication date of its first edition (1951) indicates that it had to exist prior that date [9].

Less than two decades later, in 1964, for the purpose of Vienna International Garden Show (WIG64), an Austrian engineer and inventor Othmar Ruthner realized the concept of a 41m high greenhouse tower (Figure 2a). According to the 1965’s article in the New York Times, he had already created at least eleven such structures across Austria and Western Germany, using both hydro- and aeroponic to grow flowers, vegetables and mushrooms. As the NYT reporter stated, “Ruthner works were a first step towards ‘factory’ production of flowers and vegetables”[10]. He himself, was sure that a further development is inevitable and that such structures are the future of advanced agriculture, especially in
bleak, arid and man-made environments. In the aftermath of the WIG64, his success was spectacular – both in the commercial field and in the agricultural scientific community. In 1967 his tower greenhouses became the central feature of international symposium on industrial production of plants. Specialists from United Nations’ Food and Agriculture Organization participated in the symposium in order to evaluate the possibility of utilizing the structures in hunger-vulnerable regions [11]. This was the first time the term ‘vertical greenhouse’ and ‘high-rise greenhouse’ were used in the contemporary meaning of vertical farming. A year later, Ruthner exceeded his own accomplishments with another structure in Chorzów (Poland). This structure, 54 m high and 11 m in diameter, was the largest of its kind in the world. Unfortunately, none of the abovementioned structures had been documented well enough before they were demolished, which makes any in-depth analysis difficult to conduct. The components of complicated, mobile machinery that was the true heart of the Ruthner greenhouse towers are still up-to-date and present in the modern inventions in vertical cultivation.

Figure 2 a-b-c. The vertical farms idea evolution, a) Othmar Ruthner, WIG64 vertical farm, Vienna International Garden Show, 1964 [10], b) Ken Yeang, Mesiniaga Menara (IBM headquarters tower), Kuala Lumpur, Malaysia, 1988-1992, c) Ken Yeang, Nara Tower project, Tokio, 1994, c) Ken Yeang & TR Hamzah Architects, EDITT Tower, Singapore, 2008-2017 [12]

Although Ruthner continued his inventions until early 1980s, the concept of vertical farming sensu stricte was somehow put aside and almost forgotten. In the 1994, it has surfaced as part of Rem Koolhaas’ manifesto, but in terms of a vision, rather than a solid concept [6]. More efforts on this subject have been done by another architect Ken Yeang. His Mesiniaga Menara Tower (headquarters of IBM) in Kuala Lumpur (1992) was the first to bring low-energy use to a high-density urban environment, reflecting Yeang’s idea that only the sustainable development of cities can accommodate the world’s population growth (Figure2b). Yeang was the first architect whose interest in bio-climatic and sustainable design has led to his participation in the 2007 “Visions of the Future” project, a part of the “Skyscraper! Achievement & Impact” exhibition [12]. Yeang’s works however, including in e.g. the Tokyo-Nara Tower are focused on incorporating the vegetation component into the structure and their coexistence as parts of a joint ecosystem (Figure 2c), [13]. According to Yeang, a bioclimatic vertical skyscrapers should have active building envelope, adjusted to local and the season climatic conditions. One of his most recent projects, a 26-storey open structure called the EDITT tower, is under construction in Singapore now (Figure 2d). This building was created to rehabilitate an urban, non-organic site where the natural ecosystem has been completely devastated. The vegetation areas are designed to be continuous and to ramp upwards from the ground to the uppermost floor. Although aesthetically they are unconscious reminiscences of Ruthner’s tower, they do not strictly share its purpose as the remedy for food security issue.

In 2000 Dickson Despommier, a professor of environmental health sciences and microbiology at Columbia University (New York City), modernized the Ruthner’s idea of vertical farming. Being part of an academic program at Columbia University (New York City) Despommier has modernized the
idea of vertical farming in that matter [14]. Nowadays, the idea of producing crops and breed poultry in separate or multi-family high-rise buildings is taken around the World.

3. Controlled-environment agriculture and Vertical Farming

The modern ideas of vertical farming utilize a variety of indoor farming techniques and sophisticated technologies that make up the controlled-environment agriculture (CEA) technology, where all key environmental factors can be controlled with a great precision. The aim of this technology is to provide protection and maintain the most optimal growing conditions in order to improve the vegetation cycle and yields. Complete CEA technology utilization requires sealed conditions, where it is possible to fully control such cardinal aspects of cultivation like exposure levels and time, temperature, humidity, levels of nutrients, growing medium composition and air composition. The technological advances of recent decades enable the automation of the process which not only further improves the water, energy, space and labour consumption, but also provides a better sanitary protection and safeguards crops stability. But although CEA requires a great amount of interdisciplinary knowledge – varying from chemistry, biology, through plant pathology and physiology, to IT and production chain automation, it enables the truly industrial-scale horticultural production, much more efficient and independent from environmental factors than traditional farming and greenhouses.

3.1. Different cultures – different mediums

The role of advanced cultivation techniques in CEA technology is best represented by growing number of Japanese plant factories and recent commercial success of a Newark based company Aerofarms (NJ, USA), which claims its horticultural solutions are 130 times more productive (per square foot) than a traditional commercial field farm. Their impressive optimization of resources consumption is worth mentioning, as Aerofarms claims their technology needs ca. 95% less water than traditional field farming and ca. 40% less water than traditional hydroponics, [15]. This advantages of advanced soilless cultures like nutrient film technique (NFT) – popular hydroponic technique in Japan, and aeroponics can be combined with fish farming (aquaculture) into so-called aquaponics, where fish by-products are fed to bacteria cultures which process them into nutrients for plant culture. Another, very promising branch of controlled environment food production is also edible algae farming, especially if combined with abovementioned aquaponics. Taking into account high nutritional values of edible algae, e.g. spirulina or seaweed like Pyropia, the advantages of such direction are worth the efforts. Although the specific requirements for different cultures and species within them vary, all of mentioned cultures have a common ground and in some extent are complementary. Algaculture was based on natively sea organisms is a water based culture (same as aquaculture) and requires sunlight, carbon dioxide and minerals to grow as the majority of edible algae are autotrophs, just like plants. Enabling the possibility of combining all of them in one joint CEA driven facility to produce diverse food products in one place.

One of the most crucial factors for all of the three above mentioned cultures - plants, algae and fish, is access to the sunlight. The utilization of natural daylight for cultivation purposes has obvious, significant drawbacks and restrictions: its levels depend from geographical position, season and weather conditions, as well as the amount of access (especially for IR and UV wavebands) enabled by building envelope. On the other hand, shifting from natural daylight to artificial SSL (sole source of lighting) based on fluorescent lamps (FL), high capacity enables all-year-round production cycle and adjustment to specific conditions based on the cultivated specie’s demands. It enables the maximization of yields and reduction of the overall growth cycle. Although in the Japanese experience in PFALs (plant factories with artificial light source) with the fluorescent tube lamps is impressive extended studies that have been conducted by NASA for over 30 years show that the future of industry is in LED based solutions [16]. The unique LED lamp capabilities of staying relatively cool and combining a wide spectrum of light (through the array of diodes with different colour/wavebands) enables not only energy and space savings, but what seems much more important allows to precisely
control or rather to program the growing cycle and therefore to modify some particular attributes of the plant and/or its fruits. "If quality attributes related to appearance, flavour and aroma, and nutritional well being can be manipulated and controlled by the spectrum of growth light, specialty crops produced with specific light prescriptions may have competitive advantage in the marketplace with field-grown produce shipped from afar. This form of value added goes beyond ‘local grown’ and ‘freshness’ and is an area of intense research interest”[17].

The very rigorous requirements for successful controlled environment farming exceed far beyond just cultivation techniques and adequate exposure. Precise climate control in terms of air purity, humidity, temperature and proper levels of O₂ and CO₂ in the proper phases of metabolism (especially important for autotrophs to enable the photosynthesis process) are yet another crucial aspect of CEA. The state of art control is usually achieved not only by advanced and dedicated HVAC systems, but also by special equipment and environmental sensors installed in the farming space.

3.2. CEA facility layout rationale for sky farms

As a relatively young production system, vertical farms with SSL (or PFALs) are in a constant development process, therefore the existing models have to be treated as case studies for further improvement and research field to define the optimal program and layout for future unified standards. As for now there are no international or nation-specific laws or codes regarding this particular type of facilities. Moreover, the professional literature on this matter is also rather sparse. This forces the adaptation of already working solutions from other akin facilities, like microbiological laboratories (regarding the biological safety and air purity) and traditional food processing plants (regarding sanitary standards for harvested goods and their further processing) to meet the rigorous standards inevitable in food manufacturing (ISO22000 and HACCP).

Taking that into account, it is important to identify the essential components of CEA facilities. Based upon the achievements of Japanese PFALs [18] and Aerofarm’s recent advances in depot-based vertical farms, there can be distinguished three basic tiers regarding to the functional objective: tier I – culture area, tier II – operating area and tier III – support features.

The keystone that links all of them is the abovementioned fundamental concern for biological safety. The connection (access points) between them and to the environment should be provided by air and man locks (with sanitary stations), to preserve the controlled environment conditions and to prevent the air contamination with unwanted biological material, like bacteria, viruses, fungi, pests etc. This constitutes that the HVAC systems also should have separate air circuits with different treatment measures and specified sequence of air flow in order to provide an adequate level of air sterility to the proper zones.

As a core component of CEA facilities culture area occupies the largest share of total area of VF facility. In contemporary most popular layout – depot-based plant factories, it takes up to ca. 3 times more space than the operating area tier, although taking into account the possible further automation of the processes this 3:1 ratio should be significantly greater. The main part of the tier is occupied by cultivation: growing trays stacked on the shelves, seeding, seedling and germination space. It also provides area for initial segregation, cleaning, washing and packaging of harvested food products. Operating area consist of accompanying functions including sterilization space, R&D, administration, sanitary features – locker-, wash- and restrooms for workers, as well as packaging, cool and shipping spaces for ready products. Tier III contains all building maintenance spaces, like HVAC modules, gray-, rain- and storm-water systems, power generators, batteries, green energy systems, building and culture area control rooms.

4. The Harvester concept

The contemporary plant factories, despite of the recent efforts, do not address the most important aspects of the food security problem in urban areas – its scale and complexity. Producing some of the
food is simply not enough anymore. As the studies show[1] [2], the core problem is not only in the production rate itself, but also in the defective supply and distribution chain, retail as well as in the carelessness of the end customers. All of that causes extreme rate of food loss in the process. Depending on the economy, ca. 40% of all food products is wasted either in the transportation and retail stage (undeveloped and developing regions) or in the households (developed regions)[2].

While most of the agricultural production takes place in rural regions of the globe, while the majority of its products is consumed in the highly urbanized areas. Over a half of the population already lives in the cities, and by the year 2050 it will exceed 70% including the growth of the global population up to 9.1bn of people. Moreover, it means the 60% gap in global food demand will have to be filled, [2]. Long-range transportation, which produces additional GHG pollution, especially increases the consumption of fossil fuels and therefore CO₂e emission rates, is an integral and inevitable part of this problem. The intermediate stops between farmland and the final destination – food processing, manufacturing and retail facilities are yet another important aspect of this issue and source of further pollution.

The obsolete model of food production, cannot be replaced with rather small scale of current plant factories. They are undoubtedly an important step towards the ultimate solution, but to tackle the problem they have to be taken to the next level.

The direction indicated by works of Ruthner, Despommier, Callebout and other visionaries of vertical farming concept became a cornerstone for the Harvester project – an attempt to redefine the role of vertical or rather sky farming in the nowadays society and city space, providing self-sufficiency and independence in the matter of food security for highly urbanized areas (Figure 3).

The challenge was not to create an entirely new solution, as reinventing the wheel would be pointless, but to envision the necessary conditions and a combination of solutions that would unleash the full potential of vertical farms of the future. In the paste of this considerations an important aspect of the design emerged.

![Figure 3. The Harvester architectural design: the schematic concept farming megastructure and its view of the city skyline](image)

The social acceptance of this totally new facility will be depending not only on the visual perception, economic advantages and public awareness of food source secured, but as in case of the most of new urban investments (like civic buildings, shopping malls, parks, infrastructure) it will also be depending on the additional value added to the citizens’ quality of life. Therefore it became one of our key objectives to develop a design which would create a positive by-product improving a day-to-day comfort of living in the cities.
4.2. Urban constrains

One of the important issues identified in the initial design stage was embedding the sky farm concept into the existing urban context, particularly into the Shanghai’s city grid. The considered industrial-scale of a single structure – able to provide the alimentation for a significant part of a multi-million city, and the current situation, where most of the plots in the inner-cities and city centres are already occupied with buildings, forced us to rethink the idea from scratch. The colossal scale of the initial sky farm layout (roughly 785m with over 600m of its height reserved just for the purpose of culture area) pushed us towards searching inspiration for the solution in natural environments. We were looking for the analogies between city as an organism and city as an ecosystem and noticed some parallels between highly urbanized areas organisation patterns and orderly layered nature of forests. Further studies of that subject inspired the idea of an elevated structure referred to the tropical rainforest trees and their aerial roots.

Building façade design can be divided in two main parts – the lower nontransparent supporting structure and the upper transparent envelope of the main building body. Both are an example of active façades based on regular triangulation and subdivision of the surface. Although the evident difference in the structure, both parts of the envelope function is strictly related and they must be considered as a one joint system with the internal core shaft of the main building body. As mentioned before the lower part of the envelope serves as a control component for air purification and water absorption system in the supporting tentacles. At the same time the upper envelope controls the airflow of the farming section of the building. The overall principle of the described below, while a detailed mechanics of lower active envelope are illustrated and described in Figure 4.

![Figure 4. The Harvester design: functional and structural diagram](image)

1. First, air is purified from NOx by photocatalysis by TiO2 enriched panels. 1b. Opening façade panels in a controlled manner causes an increase in air flow, which allows to regulate not only the amount of water and air provided to the building but also the level of treatment of the ambient air.

2. The main duct to increase air flow. Horizontally disposed a turbine to generate additional energy to power the building. 3. Air flow is increased or decreased by throttle at the base and at the top of the shaft. 4. From the main duct air is distributed to the each floor. 5. The double façade elements. 6. The twisted main structure results in a better flow of air. 7. Made of translucent photovoltaics façade reduces the demand for artificial light. 8. TiO2-enriched cladding and glazing provides continuous air purification form NOx.

![Figure 5. Active envelope of the Harvester vertical farm](image)

Gaps between closed façade panels enable limited airflow, therefore a smaller amounts of air and water are purified and provided to the building.
First, air is purified from NOx by photocatalysis by TiO₂ enriched panels (Figure 5), then enters the inner space of supporting structure. After being purified from particles by active carbon filters, air gets into contact with special absorbent sheets of Carbon Capture System. After this stage, a significant drop in CO₂ levels (between 20-80% of its initial rate, depending on open-closed state of cladding) can be observed. The liquid CO₂ is then recycled both as a fuel and material for production of carbon nanofibers [19]. Purified air, yet still humid, flows through water absorbent foam mesh, where condensation process occurs. Thus obtained water is then collected in internal water supply system, treated and used for all purposes. Finally, clean, dehumidified air is either exhausted to the environment (providing a better air for citizens) or used directly in the building, depending on purpose and the stage of cultivation cycle. While the decreased levels of CO₂ are always desirable for occupied levels, for the cultivation floors, the situation looks different.

Figure 6a-b. The Harvester architectural design: envisioning the harvester tower within Shanghai downtown and section through the main body of the Harvester vertical farmland and overall view. The main body is based on truss-tube two-layer structure. Due to seismic issues and wind loads, the inner structure is separated with dampers and isolation bearings to prevent dynamic shock and dissipate vibration. A 30 stories high, with just about half of them intended for modern cultivation methods like hydro- and aeroponics, single Harvester is able to provide food for over 600,000 people. Which is an equivalent to 1260 km² of traditional farmland.
The supporting structures, due to their appearance called also the supporting tentacles, fit in between the existing city grid, while the massive main body of the Harvester levitates above the existing skyline. Consequently, the concept, designed as universal solution, can be adapted to the specific, local constrains, regardless the location. But the consequences of elevating the main building body with supporting tentacles (ca. 395m above the ground) are far more important than just adjusting the design to urban constrains. As they are supposed to mimic the aerial roots (rather the velamen-based Orchidaceae species roots), with the help of cutting-edge technology they are also responsible for vertical communication, water absorption and air purifying.

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4.3. Adopting the III tierd CEA facility layout

The elevated main building body accommodates the majority of the features required in the CEA facility. The lowest levels are occupied by the second tier functions – operating area with administration, R&D, sanitary spaces, access points for vertical communication (shuttle-like elevators). They are also occupied by the preparation space of harvested products, as the main features of first tier – cultivation area occupies entirely next 30 levels of the structure. Each 20 meters high cultivation storey can be stacked with up to 50 levels of growing trays. With almost 1ha area of each of the storeys the Harvester can feed ca. 200,000 people a year. The 25x25m in plan central core, the top 20 meters high module and supporting tentacles are the third tier components as they host all necessary maintenance systems, including alternative power sources, air and water management systems (Figure 6b).

4.4. Tier IV - the positive by-product

The complementary functions, including food processing features, waste management, as well as distribution and retail located in the lowest and underground levels of supporting tentacles are meant to improve the overall impact of agricultural production on climate change, by eliminating the long-distance transportation component from the equation. At the same time the devices inside this supporting structures utilize a combination of advanced technologies – photocatalytic active building envelope’s cladding, active carbon filters and CO₂ capture system, to purify the air in the environment. The scale of the Harvester and the presumption that there will be at least several such megastructures located in the city allows to assume that they will have a great impact on currently alarming state of air quality in highly urbanized areas like Shanghai (Figure7).

5. Results and discussions

The design path chosen in the Harvester concept which defines vertical/sky farms as mass-scale food plant embedded directly into the city grid, is the aftermath of O. Ruthner’s early efforts in this field. As an envision of the future of urban agriculture, it is focused on combining the most advanced technologies of contemporary vertical farming industry and cutting-edge experimental technologies of construction industry, green energy business and advanced materials yet in development. This interdisciplinary attempt outlines a brief framework for further improvement and polemics with past concepts of sky farming concentrated either on its mostly aesthetic or technical aspects, but often omitting the ultimate purpose of the core idea behind it – replacement of obsolete and soon insufficient
agriculture in the face of rapid population growth and climate change. As an experimental approach and obviously a concept, not a ready-made solution, it is not claiming the exclusivity right. It is rather a deliberate provocation and encouragement to expand the existing discussion and broaden the circle of stakeholders.

6. Conclusions
Sky farming undoubtedly will become an important tool not only in the food security agenda, but also in climate change mitigation and prevention efforts. However, the current state of its development certainly needs further improvement. The variety of design perspectives (both past and present) is a manifestation of the complexity of the subject and its interdisciplinary nature which has to be embraced by architectural society in order to become a game-changing solution and not be forgotten yet again.

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