Indoor Farming in Future Living Models

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ABSTRACT: According to a UN report, by 2050, the world's population will reach around 9.7 billion. This growth, alongside a changing climate, will strain natural resources, especially the food supply chain. There will also be issues in relation to human health, education and well-being, due to people's growing distance from food supply. Previous projects have sought a solution to these problems through vertical farming. Producing food within an urban environment suggests a different worldview for the next generation of living and a new urban lifestyle. In collaboration with SOM, this project explores the feasibility of using a network of hybrid farms to address London's growth challenges. The research included solar studies of 3 building geometries in the identified farming zones within the building. The thermal analysis, conducted in studied areas, revealed that the optimum footprint is a square geometry. As an example, the lettuce was chosen to quantify and compare the production potential, food miles, energy and water consumption between the main farming systems. The building's design maximises daylight and sunlight access in order to produce vegetables using the least amount of artificial energy. In this manner, the hybrid farms minimise energy demand, water consumption, transportation distances and land use.
KEYWORDS: Indoor farming; Food production; Energy consumption; Urban agriculture; Vertical community.

1. INTRODUCTION

Fifteen thousand years ago, there was not a single farm on the planet. Agriculture triggered such a change in society and on how people lived. Its development, therefore, has been dubbed the "Neolithic Revolution" [1]. However, today, traditional agriculture is the primary reason for 70% of water consumption and 80% of global deforestation [2]. On average, fresh food produced travels 2000 kilometres in order to reach consumers. Aside from transportation, this operation consumes additional energy for refrigeration in order to ensure supplies remain fresh. This process emits a significant amount of carbon in the atmosphere [3]. Along with agriculture, increasing urbanisation worldwide is another primary source impacting the Earth's conditions.

As the human population continues to increase as predicted to 9.7 billion people by 2050, nearly 80% of the people will reside in urban centres [4]. Together with climate change, such increase will strain natural resources, especially the fresh food supply chain. Global food production will need to grow by an estimated 70% in developed countries and 100% in developing countries to match the current trends in population growth (based on production information from 2005 to 2007). The United Kingdom, for example, uses 72% of its landmass for agricultural practices, but imports nearly 50% of fresh food consumed [5]. It is necessary to consider new food production methods in order to ensure food security and prevent natural habitats from being destroyed for new farmland.

There will also be fundamental issues related to human health, as well as to education and social wellbeing, stemming from people's growing distance from and limited access to their fresh food supply.

Considering the available research on how to offer more liveable, sustainable and flexible living models for 2050, this thesis strives to contribute to exploring the feasibility of using a hybrid farm network to prepare London living for the next generation of urban density. The purpose of the proposal is to sustainably supply food and enhance occupant wellbeing, while also strengthening the community within a built environment. This interest is shared by Skidmore, Owings and Merrill (SOM), and leads to the formation of this thesis collaboration.

As mentioned, the world is facing interrelated is-sues concerning urban environment, society and agriculture under increasing world population and climate change. As vertical farming is no longer a nascent industry, it has been known as path to resource conservation, better human health and thriving communities [1].

Producing vegetables within a building in an urban environment suggests a different worldview for the next generation of living, as well as a new urban lifestyle – in which access to fresh food supply is made available at immediate proximity.

The energy demand associated with indoor farming, however, is still higher than certain vegetables growing systems. In light of this scenario, in order to find balance between existing methods (conventional, greenhouse and vertical farm) and production, and to minimise natural resources consumption, this research has created a hybrid farm, which offers benefits mainly in 3 different scales:

• Built environment: Farms will improve air quality, decreasing pollution and noise levels. By minimising food supply distance, they will reduce the urban heat island effect, minimise travel or delivery cost, and carbon emissions. They will also positively impact the microclimate and thermal comfort.

• Community: Farms will transform food habits in London, offering a sustainable alternative to fresh food consumption, distribution and supply as well as job and educational opportunities, together with a shared area for people to enhance their sense of community.

• Occupant wellbeing: Farms will enable occupants to live closer to their food source, which will provide both psychological and physical benefits as well as visual comfort.

The interest in this topic arises from the lead author's own experience and observations: The segregation between the natural environment and its connection with people in urban centres, causes a fundamental change - when compared to rural areas - in the way people relate to their food sources. This thesis aims to provide people, living in urban centres, with opportunities to break away from the unsustainable, industrial food distribution system, and explore ways to grow and harvest their food as part of their lifestyle.

The "Tree" is a prototype of a new urban and social vision that goes beyond the boundaries of traditional environmental design, embracing a key issue associated with the sustainable future of our cities which also relates to the environmental response and performance of buildings. In addition, the "Tree" promotes an opportunity for a new living vision of the future, merging a hybrid indoor farming, residential, office and commercial typologies. To this end, an example building is created in the Covent Garden Market area of Nine Elms in London, UK.

2. METHODOLOGY

The study begins with the industry's interest in further understanding London's future living model for 2050. It is a collaborative thesis with Skidmore, Owings and Merrill (SOM), who share the interest in how to design more liveable, sustainable and cost-effective (predominantly residential) mixed-use buildings for the next generations.

The study follows the literature review and is based on the evidence that bringing people closer to vegetation can improve human wellbeing and liveability in building. However, it challenges existing literature, which primarily focuses on ornamental plants (due to lack of knowledge and initial costs) to make such a conclusion – and not considers what the outcome may be if edible plants were taken into account. In order to understand and support this hypothesis, this study is backed up by a section of researches on vegetables necessities, growing conditions and available systems, analysing precedents as well professional support to choose the most suitable species for the local climate, building's context, and growing system.

As the concept is a novelty, with no built precedents in residential typology, the solar studies were performed on site and on 3 main building shapes: circle, triangle and square; in order to evaluate daylight availability and sunlight hours reaching the identified farming zones within the building to know the most effective building form.

The study, then focused on the research process and improvement of the selected square form's performance to minimize the use of natural resources in the farming zones, and to further develop environmental strategies for both the residential and office areas.

Consequently, thermal analysis was conducted in both the farming zones as well as the residential and office areas to determine the most effective thermal strategy.

Finally, one vegetable – lettuce – was chosen to quantify and compare the production potential, food miles, energy and water consumption between the four main farming systems (i.e. conventional, greenhouse, vertical farming and hybrid).

3. ANALYSIS AND RESULTS

Over the past decade, people's attitude toward vegetables has changed. Suddenly people are eating vegetables voluntarily, and not just because they feel they should. This change can be observed the growing popularity of vegetarian diets, and the new generation of millennia claiming a cultural shift in their eating habits. People's already changing relationship with fresh food brings more relevance for the urban farms to be built now, rather than anticipated in the future.

As this thesis chose London as the context, the inhabitants' eating habits and production systems were analysed to create 2 groups of the most consumed vegetables. These groups combined species, which could be grown under the same conditions, and with the same hydroponic system. Because each vegetable has different nutrient, water, light, CO_2 and temperature requirements, just 1 representative vegetable of each group was assessed: the lettuce was chosen from the "cold" group, and the tomato was chosen from the "warm" group (Fig. 1).

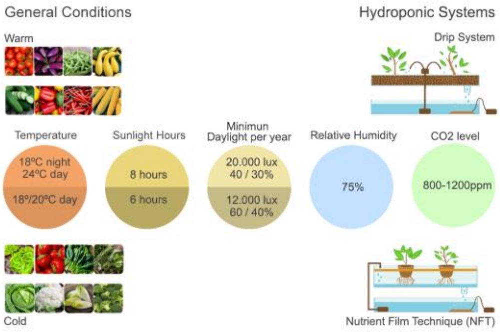


Fig. 1: Diagram with vegetables' general growing conditions.

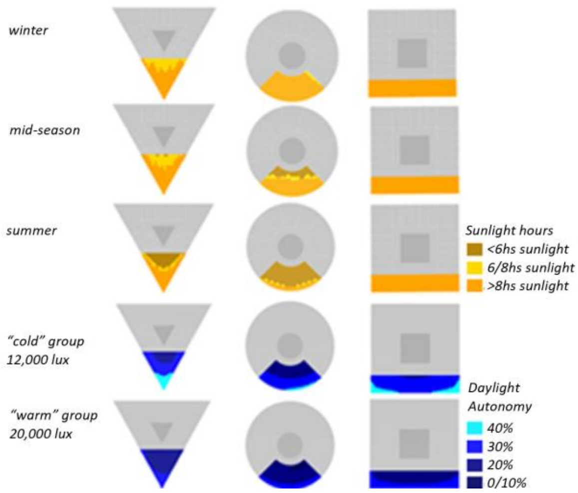
Shadow simulations performed on site showed that sunlight hours greatly vary depending on the season – even when optimum conditions can be created for an indoor farm with minimum obstructions from the surrounding context (which is likely a challenge in a dense city environment such as London). During summer, sunlight hours are the longest with approximately 10 hours or more throughout the day. During the transitional seasons, the selected project site receives between 8 and 10 hours of sunlight per day. However, there is a sharp contrast between winter and summer sunlight hours: in winter, a maximum of 8 hours of sunlight reach the project site, as the shadow range analyses concluded. The winter and mid-season analyses were superimposed to identify the best zone for the indoor farming, because it is in these seasons that the sun angle is low, likely resulting in increased overshadowing from the surrounding obstructions/context.

Integrating indoor (vegetable) farming into a mixed-building typology introduces a whole new set of architectural design considerations. In an effort to reduce energy consumption and the building's overall environmental impact; daylight, natural ventilation and a geothermal system were identified as the primary strategies and 'infrastructure' for this new kind of building. Daylight and solar access are maximised to respectively reduce the use of artificial lighting and heating demand.

The first solar analysis on the building was based on the analytical studies of 2 of the main variables that define the productivity of indoor farming. The analysis was conducted according to each vegetable group's growing conditions: The "cold" group needed 6 to 8 hours of sunlight for effective cultivation, whereas, the "warm" group needed more than 8 hours of sunlight. The careful assessment of building forms and orientations concluded that the square shape, facing south offered the ideal combination of typology and orientation, yielding to 100% productivity/year (Fig. 2).

The Daylight Autonomy analyses were performed with the threshold defined by the "cold" group's (growth) need of at least 12,000 lux, and the "warm" group's need of 20,000 lux (Fig. 3). The analyses showed that the square building form was the most effective of all, even though a slight advantage could also be observed in the triangular building shape. The analysis revealed that the square form received >12,000 lux in 11m² more than the triangular building form, and it also had 40% more effective daylight (for the "cold" vegetable group") throughout most of the year. In addition, the square form had a larger area of 142m² (when compared to 102m² in triangular form) with adequate daylight for 30% of the year. At the 20,000 lux threshold – ideal for the "warm" vegetable group – the square shape continued to perform better, with 30% of the year of effective daylight, and in 26m² more daylight area than the triangular form.

The circular shape had the worst performance for both the "cold" and the "warm" vegetable group needs, receiving 20,000 lux up to 10% of the year in 7m² of area.



Figs. 2 & 3: Sunlight Hours and & Daylight Autonomy Analyses Results

The second part of the research seeks to improve the square building form's performance and its final design. The workflow was divided into 4 main parts (Fig. 4), starting from the square form's original shape as the base-case scenario with a building area of 14,400m² - where the farming zone's effective production area accounted for 1,800m².

The building façade was slightly tilted (until the 10th floor) to optimize sunlight access to the indoor farming increasing the productive area in 630m². The respective floor plans on those floors were also retreated to maintain the residential/office area.

The third step of the study focus on to use the 3,600m² along the Northern facade for offices. Lastly, the upper part of the Southern façade was studied in detail to meet the indoor farm's needs (along that façade or orientation).

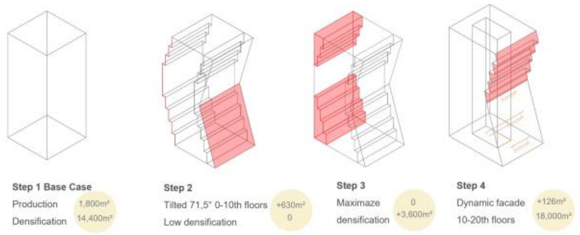


Fig. 4: Square geometry workflow diagram

The farms compared across different scenarios have double height to ensure the growth of all possible vegetables, in all the farming zones throughout the building. The base case scenario was evaluated at sunlight exposure through the sun angles at 12:00 (summer solstice 62°, mid-season 39° and winter solstice 15°), in which summer as the highest angle was used to limited the farms depth to guarantee sunlight access thought out the year. This scenario presented 1,800m² of indoor farming zone, with an area of 9,982m² to be densified in a building with 20 floors.

Naturally ventilating the indoor farms through stack effect will help reduce energy demand and costs associated with heating and cooling as well as maintaining the CO_2 and humidity levels at desirable levels. In addition, the geothermal system will minimise energy consumption in winter, as the "warm" group vegetables need artificial lighting and heating for 8 hours per day (Fig. 5).

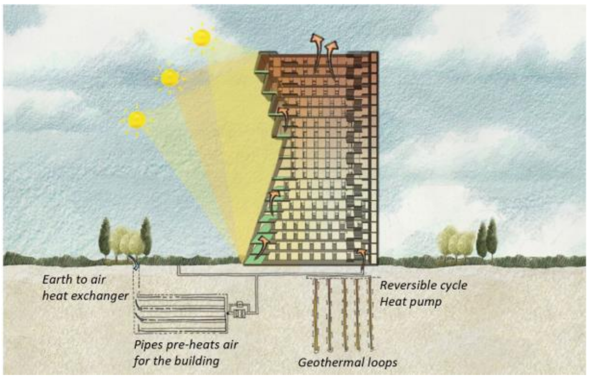


Fig. 5: Bioclimatic section of the proposed indoor farm's winter strategy with geothermal system

The south-facing farm facade is designed using a different treatment when compared to other, non-farm containing building facades: the first 10 stories of the building follow the greenhouse rule with the (city) latitude + 20 degrees: 51.5 + 20 = 71.50 degrees, and with the depth according to the summer solstice which is 6 meters (Fig. 6). As the sunlight penetrates into the farm (mostly when it has zero incidence angle), in the second 10-storey section of the building (from the 10th to the 20th level) the facade becomes dynamic, and is designed perpendicular to the summer, autumn and winter solstices.

Fig. 6: Solar access diagram in the summer solstice, mid-season and winter solstice and dynamic façade diagram.

Four different façade scenarios were modelled: the square volume as the base case, which is inclined 15° for winter, 39° for mid-season, and 62° for summer. The analysis was performed using Thermal Analysis Software (TAS) by Environmental Design Solutions Limited (EDSL) to establish a database and understand the solar gains of a dynamic façade when compared to the fixed façade. The simulation results showed a highly positive strategy for a façade that varies with seasons.

The analyses were performed during one representative week of which season. During the summer (3-09th of August) showed the best effect with 1,755,776 Watts of solar radiation/energy, which was 17% larger than what the fixed façade presented for the same period around at 1,504,565 Watts. However, during the winter (04-10th of February), the solar radiation/energy decreased by 10% (1,223,513 Watts) when compared to the base case scenario at 1,113,362 Watts. The mid-season (14-20th of April) results, on the other hand, have shown 15% increase with 1,339,180 Watts more solar radiation/energy when compared to the base case scenario. It has therefore, been concluded that the strategy was effective to increase the production within the indoor farms.

Cross-ventilation is considered to provide convective cooling in the residential and offices areas of the building. Additionally, external fins were integrated into the proposed building's facades to provide shading during the summer season, and to create a 'buffer' zone during the winter period (Fig. 7). These fins have different density and glazing ratio based on the enclosing programmes behind and the building's orientation. They were also designed with different U-values to align with the Passivhaus Standard requirements for thermal performance.

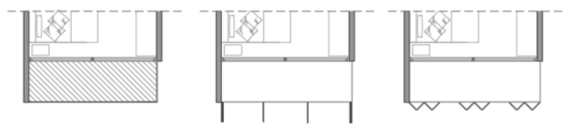


Fig. 7: Seasonal, operable external fins and the enclosing space behind

4. CONCLUSIONS AND NEXT STEPS

The research presents the theoretical background and analytical approach to the design of a future living model (for London), suggesting the "Tree" as a hybrid urban farm, delivering social transformation by reshaping the future of urban living. It offers a sustainable alternative to consume, distribute and provide a healthy food source, while also offering a shared area for local community cohesion (Fig. 8).

Fig. 8: Internal perspective of the proposed building's ground floor area

In this research, analytical studies were performed in two, main variables, which define the productivity of indoor farming. These studies which looked at 3 shapes, have leaded to an optimum building form – the square shape. The daylight autonomy analysis also revealed that the most productive building form is the square shape, because it allows for effective daylight penetration, and solar access for both vegetable groups throughout the year.

Moreover, the conducted sunlight hours' analyses confirmed the favourable benefits of the southern orientation – leading to the location of the indoor farming zones, in the final proposal, along that orientation.

The building's square form, and its indoor farms were designed to maximise passive strategies to reduce its energy consumption, greenhouse gas emissions, transportation distances, and the overall negative impact stemming from the agricultural industry. This square geometry also provided a healthy, alternative food source for the increasing urban population – re-establishing the local food sovereignty, and producing O_2, while also capturing CO_2.

The lettuce was chosen as the vegetable to investigate for this thesis. Lettuce's productivity was calculated exactly as 188.12m² area (total farm area divided by others listed vegetables), which requires natural light for 75% of the year, and artificial lighting for the remainder time (when daylight and sunlight conditions in winter, are not able to meet the lighting demand for this lettuce's healthy growth).

According to the Free-Range Practice Guide [6], one person consumes 18g of lettuce per week, totalling a demand of 864g per year that the indoor farm would have to supply for each of the 456 occupants of the building's private residential area, or 393.9kg per year. However, this result does not fully correspond to the actual lettuce consumption, since the above-mentioned amount assumes that each person eats lettuce every day, without any exceptions, for an entire year. The assessment results of the lettuce production area of 188.12m² were grouped based on two variables: the period of full sunlight exposure, representing the summer solstice and mid-season, and the period of limited sunlight exposure (which would require the aid of artificial lighting), as in the case of winter.

During the summer season, the farm area was able to produce 376.3kg of lettuce following the figures demonstrated by Graamans et al.'s research which compares the lettuce production performance in plant factories and greenhouses in three different climate zones and latitudes [7]. The farm was even more productive, with complemental, artificial lighting, capable of yielding 517.3kg during the winter period.

Assuming that natural light is available for 75% of the year, while artificial lighting can compensate for 25% of it, the annual lettuce production that the proposed indoor, hybrid farms can total up to 411kg throughout the year. Such lettuce production is not only able to meet the hypothetical demand of 393.9kg for all the proposed building's residents within the private residential area, but also to offer 17.1kg of lettuce per year for the local neighbourhood community as well as the people, who work in the building's office areas. Considering this, the "Tree" presents a successful proposal (from the lettuce production and demand standpoint) with 2.2kg/m^2 of lettuce production per year.

The thermal performance achieved with the proposed indoor, hybrid farms (evidenced in the results obtained from comparing the various urban farming systems) could be an answer to a sustainable and self-sufficient living in the growing cities. The hybrid system produces 28% more lettuce in comparison to the conventional system. In addition, this system consumes 250 times less water, and results in 47 times fewer food miles. However, the vertical farm system offers 56% higher lettuce production than the proposed, hybrid system, which in contrast, demands 46 times less energy (due to the maximised daylight access) (Fig. 9).

The strategies applied in the proposed building's residential and office areas had an overall comfort frequency (during occupancy hours) calculated according to ASHRAE Standard 55, 2013. Cross-ventilation provided effective results during Summer due to low cooling loads. The building's concluding heat demand was 3KWh/m² higher than the thresholds identified within the Passivhaus Standard, in the office typologies with buffer zones because of the high internal heat gains.

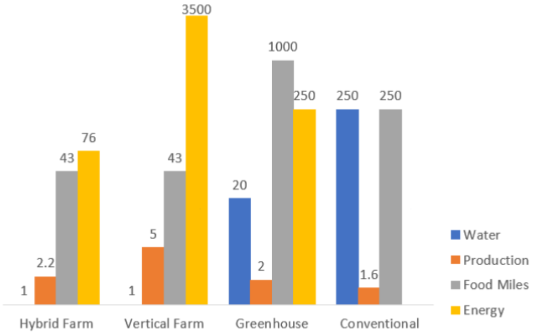


Fig. 9: Diagram comparing different lettuce growing methods

The results of the "Tree" project, presented throughout this study, were conclusive not only for the validation of a new building or mixed-use typology, but also for a new way of living. Pioneering these efforts could one day, turn into a precedent for a possible food supply solution in urban centres – using architecture as a powerful tool to stimulate community life. In addition, the proposed typology has proved to be a solution for effectively densifying new areas in cities, with similar potentials – as an action to proactively deliver sustainable buildings resilient for a changing future.

Fig. 10: Hypothetic proposal of a masterplan formed with the "Tree" concept.

The proposed typology could be replicated not only in the studied context within the Nine Elms area, but also in other areas with similar conditions – providing a new urban and social vision that goes beyond the boundaries of traditional environmental design, and embracing a key issue associated with the sustainable future of our cities (which also relates to the environmental response and performance of buildings in a changing climate) (Fig. 10). To illustrate this, the current London plan already defines 38 areas with densification opportunities (Fig. 11). Based on this context, the "Tree" could easily be spread across different scales and heights around the city of London, creating a network capable of rethinking the food system in our society.

The "Tree" concept has inherently a global vision which can spread around the world, adapting to varying climates, cultures and eating habits. With the changing lifestyles, challenged status-quo and visionary designs, such a proposal will be even more feasible in the coming years, when the imaginative and creative ability of human beings can intrinsically coexist with nature, in balance.

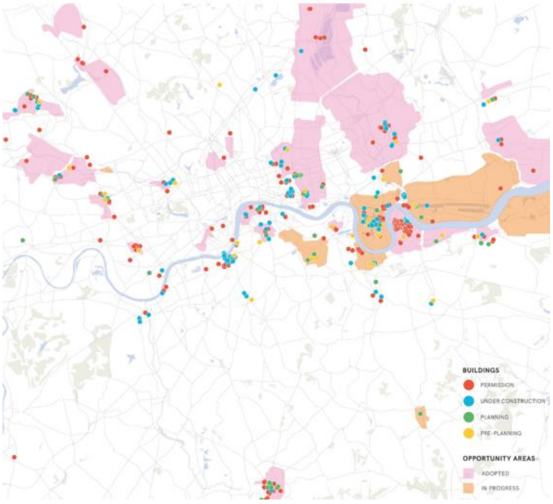


Fig. 11: Map of London's opportunity areas to be densified [8]

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