Sustainability of the 21st Century Logistics Landscape: Warehouse Roofscapes as a Potential for Hydroponic Agriculture

Tereza Nalezená
Technical University of Liberec, Faculty of Arts and Architecture, Czech Republic
tereza.nalezena@tul.cz, ORCID: https://orcid.org/0000-0003-0997-6520

Abstract: Today, the logistics landscape forms a stable part of the urban transect, where it largely shapes the entrance gates to cities. The Central European region in particular faces a massive increase in warehouse construction. In 2023, its net area reached 59 million sqm and grows by 7 million sqm each year. The paved and impermeable area of its surroundings is, however, 3x - 4x larger, which leads to a wastage of quality agricultural land and water in the landscape and to the formation of heat islands that negatively affect the climate of adjacent cities. Topically, the logistics construction is needed, therefore we must find solutions to its negative effects on the landscape, populated areas and society, and humanize their current state. One way of saving space is layering logistics with other functions. The most feasible way of using the roof landscape appears to be hydroponic agriculture - from its open form to plastic greenhouse plants to year-round RTGs using waste heat from warehouses. Hydroponic farms can be placed on most of the existing flat urban roofs due to their light weight and enable them to cool down and green up. At the same time, they can locally produce a surprisingly large number of crops per month. This can shorten the food paths, thus strengthening the food security and the overall resilience of cities. The solution is therefore based on 3+1 pillars of sustainability: economic, social, environmental + aesthetic and meets the goals of the Green Deal for Europe. However, developers and warehouse tenants are open to the idea only if it works as an independent business case (bringing new economic value), has a benefit for the company's ESG strategy or green marketing and does not create requirements on maintenance. That is why the start-up project "Lettuce on the roof", described in this article, was created as part of the research. It aims to popularize the idea, to explain its sustainability and economic benefits, to compile its business plan and thereby attract the interest of stakeholders. The project continues by the implementation of a pilot roof farm at the Technical University of Liberec, which proves the feasibility but also the economic potential, which is a condition for the roof farm quantification and expansion from small urban roofs to large roof areas of warehouses.

Key words: *[warehouse construction], [RTGs], [sustainability], [urban agriculture], [roof hydroponic farm], [soil protection]*

1 The Relevance of the Problem

The global surge in digitalization and e-commerce over the past decade, further intensified by the Covid-19 pandemic, has necessitated a substantial expansion of infrastructure to support the logistics behemoth that underpins the supply chain. In the current era, characterized by climate change, digital transformation, and the demands of the Green Deal, it is imperative to address sustainability considerations within this sector of construction. The logistics-driven data industry is responsible for approximately 2% of global CO2 emissions, a figure that is comparable to that of the aviation industry. The global production of concrete surpasses this, contributing four times more to CO2 emissions (Frejlachová et al., 2019). Logistics not only generates vast quantities of data and converts agricultural land into concretized zones and urban heat islands dominated by steel warehouses but also constitutes a unique, often overlooked segment within the urban transect. This formation, serving as entry points to cities, exists beyond the conventional scale of human settlements, presenting novel environmental, social, and urban challenges.

Figure 1 Warehouses in Zdiby (Czechia) shaping entrance gate to Prague and background to the scenic village

We must acknowledge that the massive transcontinental movement of goods, driven by consumerism, is unlikely to dissipate in the foreseeable future. Goods and food products, often nonsensically imported from the other side of the world—products which could be locally sourced—continue to flood markets. Nonetheless, logistics is experiencing significant growth: the global logistics industry was valued at USD 10.4 trillion in 2022, with projections suggesting an increase to USD 14.1 trillion by 2028 ("Statista Logistics," 2023). The demand for warehousing space in the Czech Republic even surpasses the current demand for residential areas. Consequently, warehouse parks do not vanish or undergo transformation but instead are recycled again for production and storage purposes. It is therefore critical to explore ways to manage this phenomenon, ensuring it is sustainable for the landscape and that its physical manifestations are tolerable.

The Czech Republic, positioned on the periphery of Western Europe's economic core, with its affordable labor and lax spatial planning regulations, experiences the adverse effects of this phenomenon markedly. The year 2022 was a record-breaking year in the warehousing sector, both in terms of construction and vacancy rates. Construction activities are proceeding robustly across the Central and Eastern European (CEE) region. According to the Marketbeat report by Cushman & Wakefield, the modern logistics industrial space in Q1/2024 exceeded 59 million square meters, marking a year-on-year increase of over ten percent. The majority of this space is located in Poland (52%), with the Czech Republic accounting for 21%. Per capita, however, the Czech Republic leads Central Europe with 902 m² of net warehousing space per 1,000 inhabitants, compared to Poland's 625 m² per 1,000 inhabitants. Despite a rising vacancy rate, it remains below 3%, indicating robust demand. In 2022, the Czech Republic's net warehousing space eclipsed 10 million m², with an additional million m² added each subsequent year. Current data for Q2 2024 indicate 12 million m² of net warehousing space and an additional 969,800 m² under construction (Kristek, 2024). Thousands of hectares are earmarked for development in land use plans. The rapid pace of construction and the pressure to convert agricultural land are proceeding without a cohesive national strategy, and local governments lack the legislative instruments to regulate or compel developers to invest beyond the bare, utilitarian minimum.

2 The Challenge of Landscape, Not Just Buildings...

The figures previously mentioned pertain specifically to the net area of hall buildings. Nevertheless, the paved and impervious areas surrounding these structures are approximately 3 to 4 times larger, amounting to around 40 million square meters in the Czech Republic, which corresponds to the size of a major district town. Such vast, multi-hectare complexes of hall parks, whether situated on the peripheries of cities or within open countryside, exert detrimental effects on their broader surroundings. These effects include, but are not limited to, the inability to infiltrate water, the formation of heat islands, and negative impacts on aesthetics and urban planning. A typical example is small villages around Prague, such as Úžice and Zdiby. These villages, often boasting picturesque rural centers, are now encircled by barriers of distribution center halls, which further stymie urban development, such as the much-needed residential construction.

The statistics and currently employed sustainability certifications primarily address the buildings themselves, neglecting the broader impact, particularly on soil and landscape. "*The formation of one centimeter of soil takes hundreds to thousands of years. In the context of construction, including hall parks, the Czech Republic loses up to 15 hectares of land daily. Historically, humans have relied on high-quality agricultural land, settling in locations where this resource is most abundant. Thus, the development of contemporary cities and municipalities paradoxically places pressure on the highest-quality land in their vicinity. Since 1936, nearly 1 million hectares of agricultural land have been lost in the Czech Republic, though not all due to land take. Such an expanse of land would be capable of retaining up to 2.4 billion cubic meters of water. For comparison, the annual water consumption in the Czech Republic in 2013 amounted to 1.7 billion cubic meters. This issue concerns more than merely the loss of land for food production; it extends to the mitigation of weather extremes, which the soil and its retention capacity can modulate. Developed areas amplify the frequency of climatic extremes. Some countries protect their land more rigorously, imposing stricter conditions on developers. Consequently, these developers relocate to countries with more lenient regulations, including the Czech Republic"* ("Nedej se, Země halám zaslíbená," 2023).

Discussions with warehouses developers clearly indicate a rigorous focus on economic viability, with sustainability certifications perceived as a necessary evil—primarily a competition to minimize construction costs, often resulting in buildings of lower structural integrity. Nonetheless, developers are eager to display plaques of international certifications.

"The fundamental paradox of warehouses sustainability certification lies in the fact that the apparent concern for the environment prompts the construction of increasingly new buildings. The rationale is straightforward: it is economically and temporally more advantageous to erect an entirely new hall than to retrofit even relatively recent structures to comply with certifiable standards. The guise of sustainability, under which construction

companies and developers operate, thus engenders an unsustainable and environmentally detrimental reality. Certification categories are generally lenient and readily attainable within the context of Central Europe. Virtually any property adhering to national legislative building standards can obtain a shiny BREEAM "very good" certificate. As such, certification functions more as a marketing and public relations tool, creating a facade of environmental compliance." (Frejlachová et al., 2019). This is evidenced by the article *"Accolade and Panattoni Build the World's Most Ecological Industrial Building in Cheb (Czechia)"* ("Accolade a Panattoni postavili v Chebu nejekologičtější industriální budovu světa.," 2020), which boasts an "outstanding" sustainability plaque with a record score of 90.68. However, an aerial view reveals vast expanses of developed and asphalted land within a natural landscape, where certification points are augmented by the presence of insect hotels or outdoor gyms for employees—an aspect that appears trivial relative to the scale of the development.

Figure 2 Accolade, Panattoni industrial park in Cheb (BREEAM Outstanding)

The majority of Europe employs the British BREEAM certification system for hall construction. In contrast, Germany uses the DGNB certification, which places a greater emphasis on the overall life cycle of the building, encompassing economic aspects and socio-cultural values, thereby offering a holistic perspective on sustainability. For instance, the conversion of agricultural land is not a one-off payment but an ongoing annual fee as long as the hall stands. If the hall owner ceases to utilize the property, they are obligated to dismantle the building and restore the soil to its original condition. Moreover, when the urban structure of a municipality extends to logistic parks, these parks, which would obstruct the development of the traditional urban fabric, must be relocated by the developer (in conjunction with the municipality) further from the city. Germany also consolidates logistic parks into larger clusters (Freight Villages), preventing their dispersion across the landscape. In Norway, land protection measures have been taken to an advanced level, resulting in an almost complete ban on new construction. New land development is subject to stringent regulation, and there is a strong emphasis on the recycling of existing built-up areas. Consequently, it is imperative to devise strategies to mitigate the adverse effects of warehouse construction on the landscape, urban areas, and society at large, while also exploring ways to humanize their existing conditions. These strategies must be thoroughly integrated into conceptual frameworks, methodological guidelines, and ultimately enshrined in national legislation—a framework currently absent in the Czech Republic.

3 Layering as a Strategic Approach:

Beyond the conventional elements of building sustainability (such as energy efficiency, rainwater harvesting, materials, and shading), which in the context of this study are considered relatively "cosmetic," the automation of logistic warehouse operations and the stratification of functional uses are posited as efficacious strategies for land conservation.

In particular, the automation of logistic halls has the potential to reduce the floor space requirement to a third of its original size, which is significant for multi-hectare facilities. Not only does this result in spatial efficiency, but it also confers additional benefits: areas serviced by robots (self-storing systems) do not necessitate heating or lighting. Consequently, the human-operated sections can be designed to be highly space-efficient. This spatial efficiency facilitates the vertical stacking of storage units or their placement underground. Various types of self-storing systems exist, utilizing different technologies and principles, with Autostore being the most prevalent. The Technical University of Liberec, for example, has developed the Idea Storage system.

Figure 3 Autostore self-storing system

The urbanistic concept of layering was presciently demonstrated by the famous Dutch pavilion designed by MVRDV for Expo 2000 (project initiated in 1997). Nations grappling with limited land availability, or those cognizant of its ongoing depletion, have been at the forefront of such innovative solutions, even if economic constraints have often slowed the realization of these visions. In the 1990s, various projects in the Netherlands, Britain, China, and other countries investigated the feasibility of underground logistical transport—known as Underground Freight Transport (UFT). However, these projects were frequently halted due to prohibitive costs and impracticalities (Chen et al., 2017). Given projections that transport activity will double by 2050, and the escalating demand for expedited goods movement (World Economic Forum 2023), interest in UFT solutions is being rekindled. Currently, projects like Sargo Sous Terrain (Switzerland, anticipated completion in 2031) are underway, with parallel endeavors in Britain, China, Singapore, and the USA.

Czech academic institutions, such as the Faculties of Architecture, have also engaged in exploring logistical construction innovations and the integration of logistical functions within the urban fabric. Notable contributions have emerged from Atelier Kraus – Zedníčková (FUA TUL 2021), Atelier Buček – Horatschke (FUA TUL 2023), and Atelier Valouch – Stibral (FA ČVUT 2023). These explorations have yielded a plethora of alternative logistical construction forms, such as subterranean and high-rise structures, urban integration strategies, reutilization of excavated landscapes, and multifunctional roofscapes supporting uses like hydroponic farming, greenhouses, penal facilities, residential complexes, and even fully-fledged urban districts. These innovative visions have also been promoted in architectural competitions sponsored by developers in logistics, such as Prologis 2030.

Figure 4 "Onion" project by B. Simunkova 2023 – housing on top of the logistic warehouse

The most practical and immediately feasible of these visionary concepts seems to be the utilization of extensive roofscapes for light hydroponic agriculture. This is substantiated by the fact that such projects are already prevalent in Western nations, where urban agriculture is on the rise. Incorporating residential quarters and other alternative functions on the roofs of logistical warehouses requires a substantial and meticulously designed load-bearing capacity for the entire structure. Roofs must be statically reinforced to accommodate year-round greenhouses. However, for open, seasonal hydroponic farms, even a standard roof of existing halls (with a static margin for snow load) can suffice. This approach offers an alternative space for intensive agriculture amidst the loss of arable land due to construction, while also contributing to roof cooling through greening efforts, thereby mitigating the formation of urban heat islands.

4 Rooftop Landscapes as a Potential for Urban Hydroponic Agriculture

Hydroponic agriculture has existed since ancient civilizations (the Hanging Gardens of Babylon, Egyptian, Greek, and Byzantine cultures), as well as in the Middle Ages (monastic gardens, courts, palaces). At that time, the purpose was not urban adaptation to climate change or reducing the carbon footprint but rather city resilience and food security in case of attacks. Similar community urban agriculture projects emerged during crises and wars in the 20th century. However, modern urbanism generally moved agriculture out of cities (Pons et al., 2015). In the 21st century, urban farming is rising again as a necessity rather than a trend due to increasing populations and climate change. The FAO (Food and Agriculture Organization of the UN) predicts up to a quarter of total agricultural production in cities, which can shorten food supply chains, reduce the need for packaging, and strengthen food security and overall urban resilience. Hydroponic farms can cool and green rooftops, improving the climate of hot cities and fostering biodiversity. Urban farming can be beneficial from small scales—balconies, terraces, community gardens, school projects—bringing significant social and educational dimensions, to large scales of intensive commercial farms that can utilize large areas (like warehouses) to produce surprisingly large quantities of crops. This solution relies on 3+1 pillars of sustainability: economic, social, environmental, and aesthetic, and aligns with the goals of the European Green Deal (especially the Biodiversity Strategy 2030, energy, and territorial resilience).

Light hydroponic technology (growing without soil, in nutrient solutions) can be employed in various forms and scales within cities. Open rooftop hydroponic farms produce only seasonally (in temperate climates), but they green and cool rooftops during the hottest months. The advantage is that they can be installed on almost any existing flat roof due to their lightweight and wind resistance thanks to a lamellar structure. Roofs typically have a load reserve for snow, which is unused in summer, and the farm can be decommissioned or dismantled in winter. Roofs often have a reserve load capacity for photovoltaic panels, which hydroponic systems can match, allowing for combination with solar panels and shared maintenance. This solution is particularly suitable for smaller urban farms—communities, companies, institutions—and economically offers the first (simplest and cheapest) step towards urban farming. Large farm sizes—and thus large production—can be achieved, but due to potential external influences, perfect production stability for large-scale commercial supply is not guaranteed. Even so, the production can be consumed locally—canteens (companies, schools, institutions, hospitals), communities, local catering suppliers, restaurants, bistros, farmers' markets, and so on.

Figure 5 Les Fermes Agripolis, Paris

The production season (in temperate climates) can be extended by several months by covering the hydroponic farm with a greenhouse, a lightweight and cheap solution requiring some structural preparation of the roof. This ensures farm environment stability and protection from external influences like direct sunlight, rain, hail, pests, etc. Such a solution is suitable for existing roofs of warehouses or supermarkets with a certain structural reserve, where the roof can be slightly modified and minor farming infrastructure added—suitable access, infrastructure for technologies. This farm can then produce almost year-round and is suitable for commercial-scale production. The most sophisticated form of urban agriculture are year-round Rooftop Greenhouses (RTGs), which can significantly improve the building's energy balance through insulation and consumption of waste heat (Pons et al., 2015). They can produce large quantities of crops year-round directly on supermarket or warehouse roofs but require significant changes to existing buildings and must be planned during the building's design phase.

Hydroponic rooftop farms in various forms already operate worldwide. Open seasonal farms often utilize brownfields—Brooklyn Grange, USA, for example, or the former Expo site in Paris—Les Fermes Agripolis Paris (2022), where they produce up to 900 kg of vegetables daily from March to October. RTGs have been operational for several years in Europe (Agrotopia, Belgium), the USA (Gotham Greens), and Canada, where Lufa Farms in Montreal show that year-round farming in rooftop greenhouses using waste heat from buildings is possible even in cold climates. From a typical warehouse roof, they harvest up to 14 tons of vegetables per week. Recently, a project in Western Europe, Interreg NW Europe GROOF, established four pilot rooftop greenhouses (France, Luxembourg, Germany, Belgium) for local consumption and conducted coaching sessions for additional projects across Western Europe, providing extensive data, described benefits, and challenges of building RTGs (Conseil de Développement Economique pour la Construction, 2023). In the Czech Republic and the wider CEE region, such farms are not yet commonplace.

Figure 6 Laval, Lufa RTGs Farms, Montreal

5 Project "Lettuce on the Roof" (Experimental part of Doctoral study)

The previously mentioned issues associated with extensive industrial development—such as considerable land usage, rainwater runoff, heated warehouse roofs, and long food supply chains requiring logistical support—present significant opportunities for utilizing warehouse roofs for intensive hydroponic cultivation. We recognize that these warehouses are permanent structures, but we can repurpose their rooftops to compensate for the land they occupy. This approach offers various benefits: it mitigates heat island effects, shortens food supply chains, reduces CO2 emissions, supports biodiversity, and generates economic and marketing value.

International developers and warehouse tenants are willing to consider this concept only if it functions as an independent business case with new economic value, contributes to corporate ESG strategies or green marketing, and does not create maintenance demands. This led to the creation of the start-up project "Lettuce on the Roof" within this research, aiming to popularize the research and concept, demonstrate its sustainability and economic benefits, attract corporate interest (via ESG and green marketing), develop its business plan, and capture the attention of major sector stakeholders.

Figure 7 "Lettuce on the Roof" – Startup logo

The "Lettuce on the Roof" start-up project was initiated during the Start-Up TUL competition, organized by the Student Business Club at TUL in 2023. Discussions with developers revealed their reluctance to place anything on warehouse roofs due to the additional costs and maintenance requirements. They adhere to the bare minimum compliance enforced by country-specific legislation. For instance, while Portugal mandates pervious surfaces for all paved areas in warehouse parks, the Czech Republic does not, hence investment in these areas is unnecessary there.

However, developers are increasingly acknowledging the pressure from sustainability certifications and ESG reports, requiring measures to enhance corporate social and environmental responsibility. This "green" pressure is intensifying, affecting sectors such as banking, marketing, and logistics. In the Czech Republic, companies currently manage with measures like installing photovoltaic panels on roofs, and occasionally, beekeeping initiatives to support biodiversity, which are insufficient. Although ESG reporting is mandatory only for large firms in the Czech Republic, these firms are progressively extending their obligations to medium and small enterprises, anticipating future requirements.

A further complication arises from the fact that warehouses often have different owners and tenants (operators). In the context of establishing rooftop farms in urban food distribution warehouses, each party defers responsibility to the other—the warehouse owner (international developer) cites potential tenant changes, while the tenant (market) highlights that the roof is not under their jurisdiction. Thus, the business concept must emerge as an independent entity—a third party that leases the roof from one and sells the farm's produce to another.

The business plan for the “Lettuce on the Roof” start-up was therefore designed as an independent venture utilizing established market-available hydroponic technology, supplemented with know-how for its safe installation and operation on roofs (technical roof knowledge, safety and legal assurance, maintenance, harvest, sales, etc.). For firms or entities interested in greening their roofs, the “Lettuce on the Roof” offers turnkey solutions (design, installation, maintenance, harvest) for a fixed fee.

It has been demonstrated that rooftop cultivation can yield substantial amounts of produce, more than companies could use internally (canteen or employee consumption), given that 1 square meter can produce approximately 20 heads of lettuce monthly, resulting in up to 400,000 heads per month on a typical 2-hectare warehouse roof. Thus, the concept of a network of rooftop farms emerged. This network would function similarly to community energy models, where surpluses from one farm can compensate for another's shortfall or be distributed among network participants, such as local restaurants, bistros, senior homes, or sold at farmers' markets or through subscription boxes. Various sizes of firms and institutions suitable for rooftop cultivation, as well as end consumers interested in local produce from rooftop farms, can join the “Lettuce on the Roof” network.

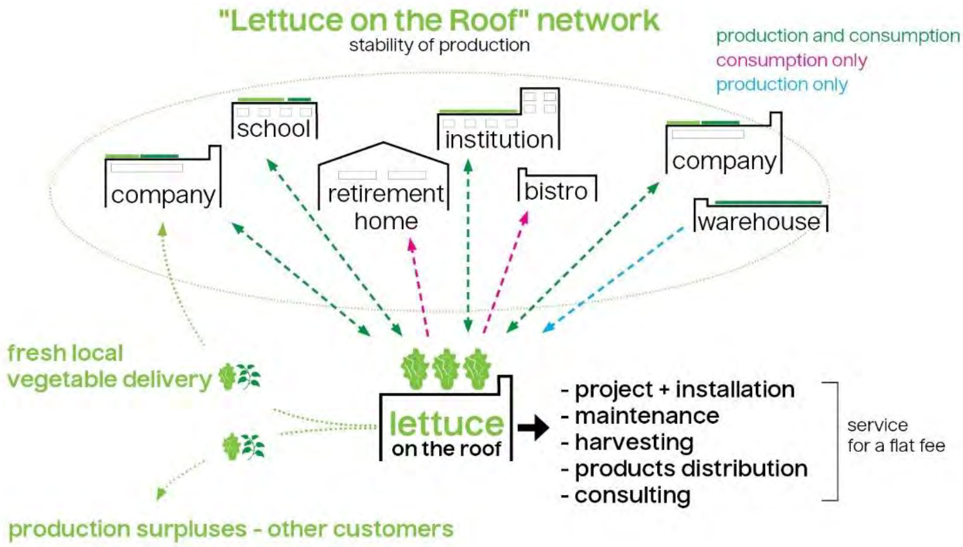

Figure 8 Lettuce on the Roof - roof hydroponic farms network principle

Illustrative Example: Consider a scenario where a company establishes and operates (for a fixed fee) a rooftop farm of 100 square meters, producing 500 heads of lettuce per week. Half of this yield is utilized for the company’s canteen and the employees, while the remaining 250 heads are distributed to local senior homes, orphanages, or sold to gastro establishments and end consumers, managed by a dedicated network. This initiative not only offers the benefits of greening and production but also incorporates a social dimension. The surplus produce can be charitably distributed to local social institutions, and there is potential for local sheltered workshops to manage indoor nurseries for seedlings used in all rooftop hydroponic farms in the area. Companies can thus enhance their marketing and ESG declarations by highlighting their efforts in greening (and cooling) rooftops, as well as caring for the health and well-being of both their employees and the community.

Another example within the project includes a university rooftop farm in Liberec, utilizing the extensive, heated rooftop terraces of student dormitories. These rooftops have the potential to produce up to 20,000 heads of lettuce on each of the six buildings. The produce would be distributed to the university canteen, local bars and bistros (for herbs), or to end consumers.

Technical Details: The "Lettuce on the Roof" startup project is based on a unit consisting of one hydroponic stand measuring 2.5 x 5 meters, containing 200 growing slots. This configuration can produce up to 200 plants (lettuce or herbs) per month. In terms of costs, the primary requirements are energy for the pump, water (rainwater can be used with filtration), nutrients (potassium, phosphorus, nitrogen), and seedlings. These seedlings can be grown in an in-house indoor nursery (with shelves, UV lamps, and a nutrient solution pump) or purchased from commercial hydroponic seedling nurseries. On the flip side, there is the economic potential of the produce itself or a maintenance fee. The startup's financial plan estimated the return on investment for a rooftop farm to be 15.4 months, considering both the peak and off-peak seasons.

Strategic Ambition: The goal was to scale up to large warehouse rooftops, ideally those directly above markets or food distribution centers, where the concept could have the most significant impact. The long-term vision includes year-round rooftop greenhouses. However, achieving this requires gradual progress—starting with a pilot rooftop farm to demonstrate operational feasibility, followed by smaller farms to confirm economic potential, which is essential for quantifying and expanding from small urban rooftops to large industrial roofs.

6 Pilot of the Rooftop Hydroponic Farm 'Lettuce on the Roof' at TUL

In the autumn of 2023, the startup project 'Lettuce on the Roof' triumphed in the SBC TUL competition, securing both support and funding to kickstart its first initiative— a pilot rooftop farm at the Technical University of Liberec (TUL). This venture is also integrated into the TUL student grant competition (code: SGS-2024-2478, Pilot Network of Rooftop Hydroponic Farms), in collaboration with TUL's Faculty of Architecture (FUA) and Faculty of Economics (EF).

The primary objective of the pilot was to establish an open rooftop farm and assess its functionality over the course of one season. The farm was situated on the flat, asphalt-covered roof of building E2, which demonstrated that a lightweight hydroponic farm could be feasibly installed on virtually any existing flat rooftop. Access was restricted to a ladder from the top floor of the building, passing through the elevator machine room, which doubled as a farm utility space with electricity and water hoses.

The farm configuration consisted of four separate racks (2.5 x 5 x 1.5 meters), each holding 200 slots, combining to a total area of 50 square meters and a capacity of 800 slots, potentially yielding up to 800 units (lettuce/herbs) per month during the growing season from April to October. Water and nutrient replenishments were performed manually, and water quality, nutrient levels, and pH were monitored thrice weekly. The farm utilized municipal water from the building supply, with a weekly consumption of approximately 1000 liters. Maintenance required about 4 hours per week.

Figure 9 Hydroponic growing rack

In addition to testing farm operations, the impact of the rooftop farm on the temperature of the roof and building was also measured. Three pairs of sensors were employed for long-term monitoring, each pair consisting of one sensor beneath the farm and one outside it, shielded from direct solar radiation. The sensors recorded surface temperatures, temperatures at a reference height of 1.1 meters above the roof surface, and indoor temperatures in two identical offices—one beneath the farm and one without any rooftop intervention.

The planned commencement of cultivation in April was delayed due to multiple factors—ensuring safety through height work training, securing collective protection around the farm (railings), resolving legal issues such as rooftop rental from the university, insurance, hydroponic technology leases, and addressing the challenging roof

access for technology installation. These primarily bureaucratic hurdles postponed the installation of hydroponic technology until the end of June 2024.
However, by April, an indoor seedling nursery (a three-tiered rack, 60x100 cm, with its own circulation and a UV lamp on a timer) and a demonstration rack with its own circulation outside the university café (holding 40 growing slots) were operational. The demo rack, located on an open-access terrace with educational information about the research, was visible from building E2's rooftop farm and supplied produce (lettuce, basil) directly to the café. After initial setbacks due to unexpected frosts affecting the initial planting, subsequent plantings thrived, and café staff eventually managed the demo rack independently, requiring assistance only for seedling replacements.

Figure 10 Indoor seedling nursery at TUL

Seedlings were grown from seeds in propagation trays with cultivation fleece. The nursery facilitated experimentation with different lettuce and herb varieties. Typically, lettuce seedlings matured in about three weeks. Fleece cultivation ensured clean production. Commercial seedlings from Germany, grown in peat cubes, proved suboptimal due to dirt residues and clogging of pumps. Herb propagation was effectively achieved by rooting cuttings in cultivation fleece. The nursery's operational reliability was high, with only one electrical outage affecting pump operation. It adequately supported the entire farm's capacity (800 slots), with minimal water and nutrient replenishment requirements and UV lamps accounting for energy consumption.
The installation of the rooftop farm, including railing installation, was completed using a crane by the end of June 2024. The main challenge was leveling the racks for optimal nutrient flow on the slightly inclined roof. By July, the first mature plants (lettuce/herbs) were harvested, typically within four weeks post-seedling. In addition to various lettuce types, the farm grew strawberries, basil, mint, and small tomatoes, although lettuces proved most sustainable given local climate and maintenance demands. From July to October 2024, the farm weathered extreme conditions—hailstorms, high winds, heatwaves exceeding 60°C, and cold, rainy days—without damage. Lettuce plants particularly exhibited resilience, with occasional blooming or leaf tip rot due to fluctuating weather conditions. No pests were detected on the roof, while beneficial insects like bees, wasps, ladybugs, and butterflies were observed, indicating biodiversity improvement. Overall, it was more pleasant to be on the rooftop among the cultivation stands during hot days than on the exposed open roof.

Figure 11 Open rooftop hydroponic farm at TUL

This is substantiated by the data obtained from the aforementioned pairs of thermometers. The surface temperature of the roof beneath the farm was up to 20°C lower (thanks to shade and water evaporation) than the temperature outside the farm. The graphs indicate that the farm mitigated temperature fluctuations on the roof. At a reference height of 1.1 meters above the roof surface, there were smaller but still significant temperature differences. Indoors, between the two identical reference rooms, the one beneath the farm was 1°C cooler, which is beneficial for the building's energy efficiency and cooling.

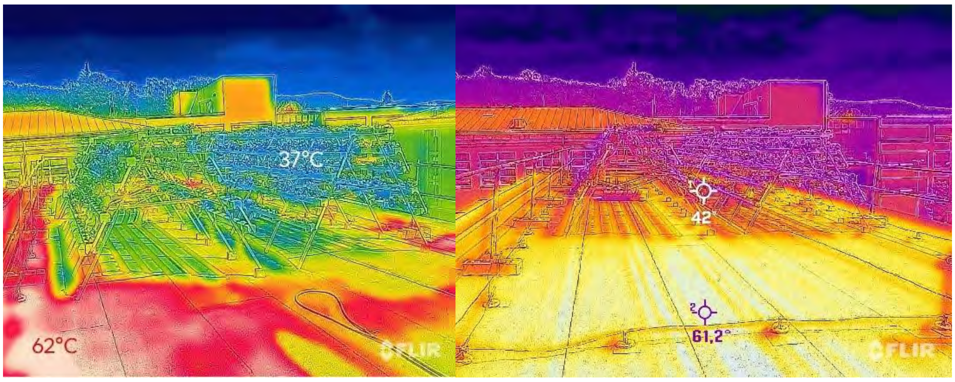

Figure 12 Thermal camera image of the farm

As part of the research project, the farm's produce was distributed to local restaurants, bistros, cafés, and senior homes for feedback. We received overwhelmingly positive responses (regarding taste, freshness, and cleanliness) and expressions of interest for future commercial orders. Feedback at farmers' markets was also positive, with many visitors recognizing the project from media coverage and social media, choosing to support us.

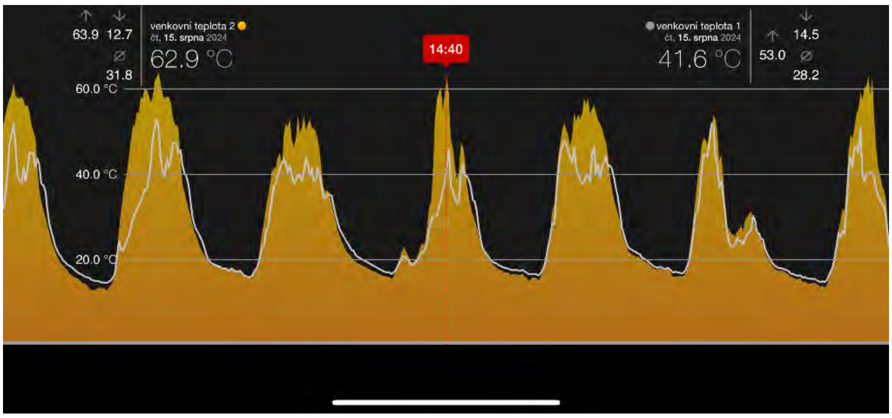

Figure 13 Thermal data- comparison of surface temperatures of an open roof and a roof under the farm

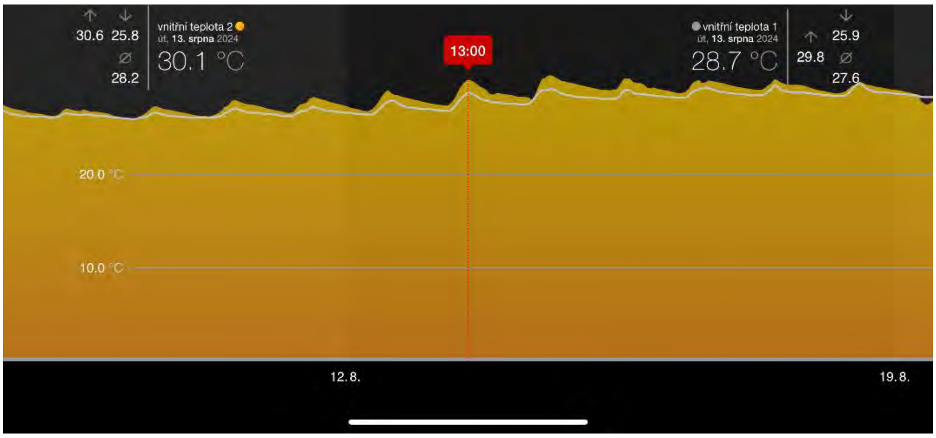

Figure 14 Thermal data- comparison of 2 identical offices interiors under the roof (lower under the farm)

One of the pilot's goals was to demonstrate the farm's operation to the general public and to popularize the concept through media outreach. This was successfully achieved through continuous promotion on social media platforms such as Facebook, Instagram, and LinkedIn, and especially through a well-timed press release in mid-August during a significant heatwave. The media outreach was substantial, attracting dozens of media outlets and resulting in coverage in print, online, on television, and on radio. This succeeded in meeting our objective, increasing public support and, more importantly, sparking interest from companies and warehouse owners, our primary targets.

In conclusion, the journey led from theoretical research to a viable concept that was successfully implemented and validated in practice. As a result of the pilot, the project is no longer confined to theory and documentation; active negotiations with companies in the city's industrial zone are underway, who are interested in establishing rooftop hydroponic farms for the next season, thus making the startup 'Lettuce on the Roof' a reality. The pilot project at the university is still ongoing as of September 2024, with final data and reports expected by the end of 2024. This research project has demonstrated the necessity of interdisciplinary collaboration to translate urbanist ideas, such as urban greening with hydroponic farms, into practice. It is essential to articulate the concept to stakeholders not only from an architectural and urban planning perspective but also through economic metrics.

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