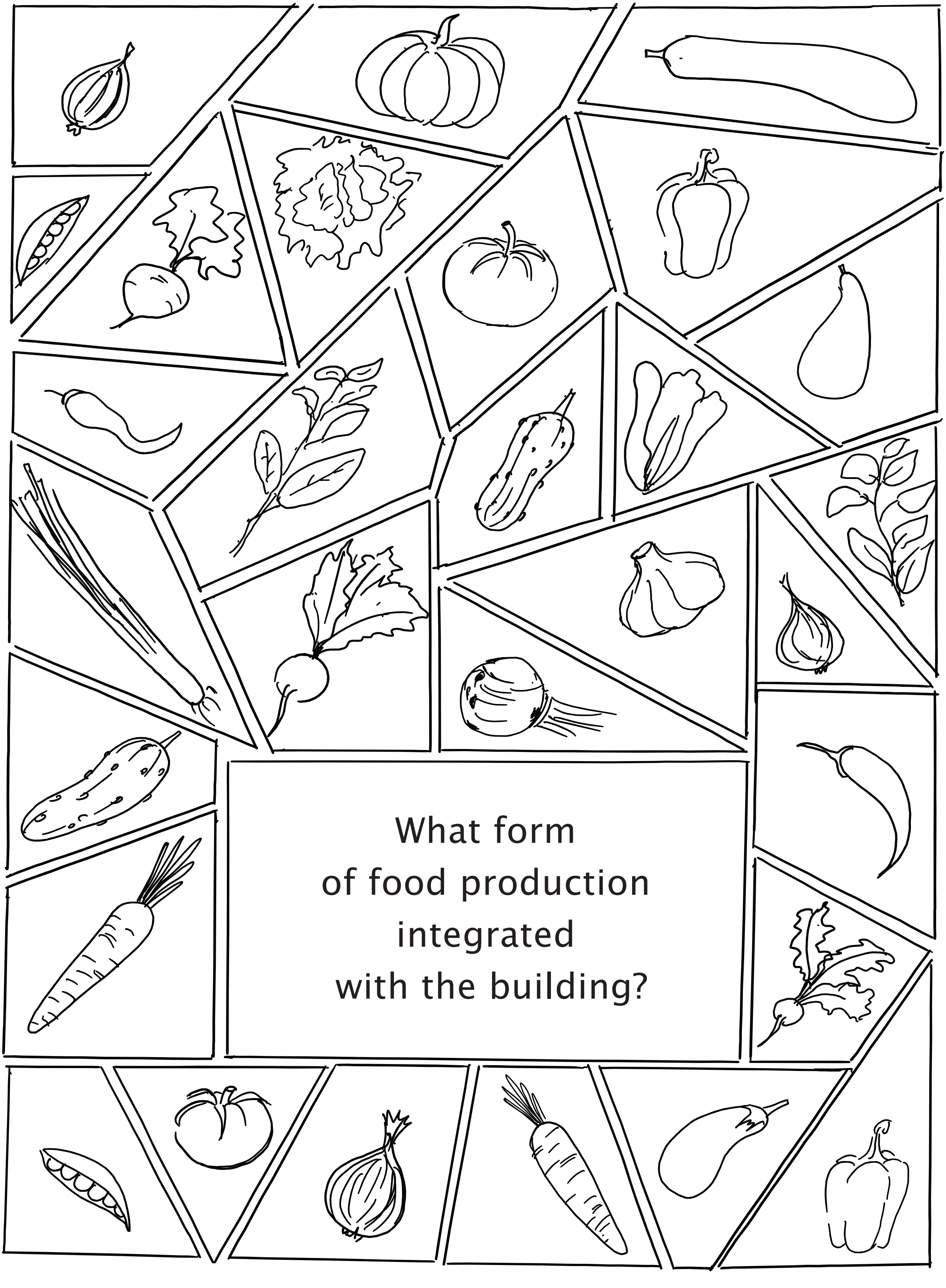
What form
of food production
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with the building?

What form of food production integrated with the building?

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We're only truly secure
when we can look out our kitchen window
and see our food growing
and our friends working nearby.

Bill Mollison

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Finally, I want to thank my husband for his support.

Contents

Chapter 1

Why care about urban farming?

The interest in urban food production appeared as a result of my fascination with permaculture, which designs resilient systems following the patterns observed in nature. Permaculture declares a holistic approach to design and tries to understand the connections between different elements of the systems. It inspired me to see architecture as an element of a larger system consisting of living and nonliving components that interacts with them in different dimensions.

Architecture design is about creating microsystems. It is important to see it as a part of a network and at a different scale - neighbourhood, district, city, etc. That is why many permaculture principles can be very helpful in architecture design. For instance, there is a great principle in permaculture design saying that every element should fulfil more than one function, ideally at least three. At the same time, another principle says that every critical need such as water, food, heating, sanitation should be provided in multiple ways. Such an approach in architecture results in functional design optimal in terms of input and output.

In permaculture, I appreciate the constant striving for optimisation: to get as much as possible through smart movements. The well-known motto of architects: *less is more* fits in so well here. To put this approach into practice, one has to follow the first and basic permaculture principle - observe.

I am treating this work as a tool to observe and analyse. I ask the question about the relation between the constructed environment and food production. Having analysed different aspects of building-integrated food production, I wanted to understand the impact of such integration. My aim was also to verify to what extent its influence depends on the method itself. The issues raised in this work are very complex and I am not going to provide one explicit answer to the question: what form of food production integrated with the building? The objective of this study is rather to give an overview of different methods of building-integrated agriculture and appraise the impact of its different forms on three dimensions: social, spatial and environmental. I wanted to develop a certain criticism, necessary for architects to shape their surroundings reasonably and consciously.

It may seem that there are more important functions to be filled in buildings than food production. After all, agriculture takes up already enormous surfaces outside the city and seems to have been doing well for years. The use of fertilisers and increased mechanisation within the XX century allowed it to considerably boost its productivity. Unfortunately, all that happened at the expense of serious environmental damages. Intensive use of chemicals has caused depletion of the soil which, as a result, requires more and more fertilisers and pesticides. At the same time, harmful effects on human health of the latter are only partly known. In many areas, the natural fertility of the soil has been lost, and its restoration, even if possible, would take many years.

The emerging problems with industrial agriculture and searching for ways of giving nature and food production back to the city resulted in a worldwide trend of urban agriculture. And in fact, urban agriculture has never before been more of interest as in recent days. Bill Mollison, a father of permaculture, already in the '70s advocated the use of every free space in the city for growing fruit and vegetables. At that time there was not so much attention paid to urban food production. The problem of soil contamination was not so widespread as nowadays, either.

The soil contamination touches 15 cm of the soil, exactly where edible plants are cultivated and constitutes the first obstacle for urban farming. The main cause of pollution spreading is by contamination of rainwater evacuated from the roofs because of the materials including heavy metals present in watertightness as well as in zinc and lead used for the edges connectors and gutters. The pollution is also carried by air and its reason is a general urban activity, pollution from houses and roads and waste incinerators.

Interestingly, soil pollution is not necessarily the case of huge agglomerations. Some new studies revealed that in Fribourg in Switzerland some private gardens in the city are contaminated and should not grow food although the city has only 38 thousands of inhabitants. The major contaminants of urban parcels include heavy metals and metalloids, especially lead, zinc, copper, and cadmium; organic pollutants such as PAHs and pesticides; asbestos and pathogens (Alloway 2004). Hence, growing plants in the soil in urban areas cannot guarantee healthy vegetables if compared to supermarket products (Säumel et al. 2012). According to the Food Standards Agency, exceeding the statutory limits set for commercial food is a rare case. The study in UK revealed that even though the lead concentration is 5 times bigger than in agricultural soils, only less than 1 sample of carrot out of 120samples of root vegetables including potatoes, carrots, parsnips, swede, beetroot, turnip, and celeriac exceeded the old statutory limit of 1 mg of lead kg of fresh weight (Food Standards Agency 2007).

Therefore, the state of the soil is an important factor to take into account to promote an appropriate form of urban farming. Some specialists on soil pollution say that there is no soil left in the cities. It has a double meaning. There is no soil of good quality but also in strongly densifying cities, there is simply very little space that could be destined for urban farming. At the same time, the demand for fresh products is growing proportionally to the increasing population living in urban areas. The answer to current problems and needs can be building-integrated agriculture. Mandel (2013) put it this way: "The hunger for local food has reached new heights."

Chapter 2

How can architecture produce food?

Building-integrated food production is a practice of locating units producing vegetables and fruit in and on the buildings. It can take various forms ranging from low-tech solutions based on the soil or simplified soilless systems to complex hi-technology installations.

Given that it is difficult to find available surfaces in the cities for food production, there is no surprise that the buildings with their free spaces — walls, roofs, interiors — became attractive new opportunities for that function. The roof offers the widest range of possibilities: from soil-based cultures to new technologies applications such as hydroponics, aeroponics, or aquaponics. The soilless technologies may exist on the roof both as open-air and conditioned facilities. The latter requires a rooftop greenhouse to grow plants all year round.

Walls are less frequently used but they also provide interesting opportunities to produce food and better the neighbourhood, the example of which can be a project Green Belly — a modular solution that constitutes a great alternative for blind walls.

Introducing food production into the building requires first of all providing appropriate lighting for plant growth. As far as possible, the plants should always benefit to the greatest extent from natural light. An extreme case of the urban food production unit is a concept of a vertical farm: a hi-technology building constructed to produce vegetables inside on a massive scale.

This chapter describes four main food growing methods integrated in architecture: hydroponics, aeroponics and aquaponics and soil-based farming.

2.1 Hydroponics

Hydroponics is the method of growing plants in a nutrient solution. The term was coined in 1937 by Gericke and initially referred to water culture without any substrates. Currently, hydroponics in the majority of sources comprises liquid-based variant and substrate-based one (to stabilise the plants) (Raviv, Lieth, and Bar-Tal 2019).

Every hydroponic facility needs a separated germination area. Germination area is a room or greenhouse where the seedlings mature under constant lighting, with closely controlled temperature, relative humidity, and irrigation. The seedlings are flooded with nutrient solution 2 to 4 times a day for approximately 15 minutes. After a given period, the fertiliser solution is automatically drained. Then, the seedlings are placed in the pond area where they spend the next 21 days until they achieve the final size. To produce about 2000 lettuce seedlings for 11 days, 250 l of nutrient solution is needed. There are 2 phases of principal growth. During this period the plants are once re-spaced from 97 plants/m^2 to 38 plants/m^2.

Commercial hydroponic production requires constant monitoring of temperature, nutrient solution, relative humidity, CO_2 concentration, light intensities from sunlight and supplemental lighting, pH, dissolved oxygen levels and electrical conductivity of the nutrient solution. Sensors detecting any undesirable measure, send signals to the control computer which in turn activates heating, ventilation or lighting. Changes in pH, electric conductivity, which is a measure of dissolved salt in the solution, carbon dioxide concentration and oxygen added to the solution in liquid require physical human action to regulate the parameters. Every plant has its specific requirements in terms of optimal parameters. It is, thus, not possible to obtain good results in polycultures (Brechner M. and Both A.J. 2014). There is a wide range of substrates used in hydroponics: from natural materials (sand, peat, coconut coir) to processed (pumice, expanded clay granules) and synthetic media (polyurethane, polystyrene, polyester

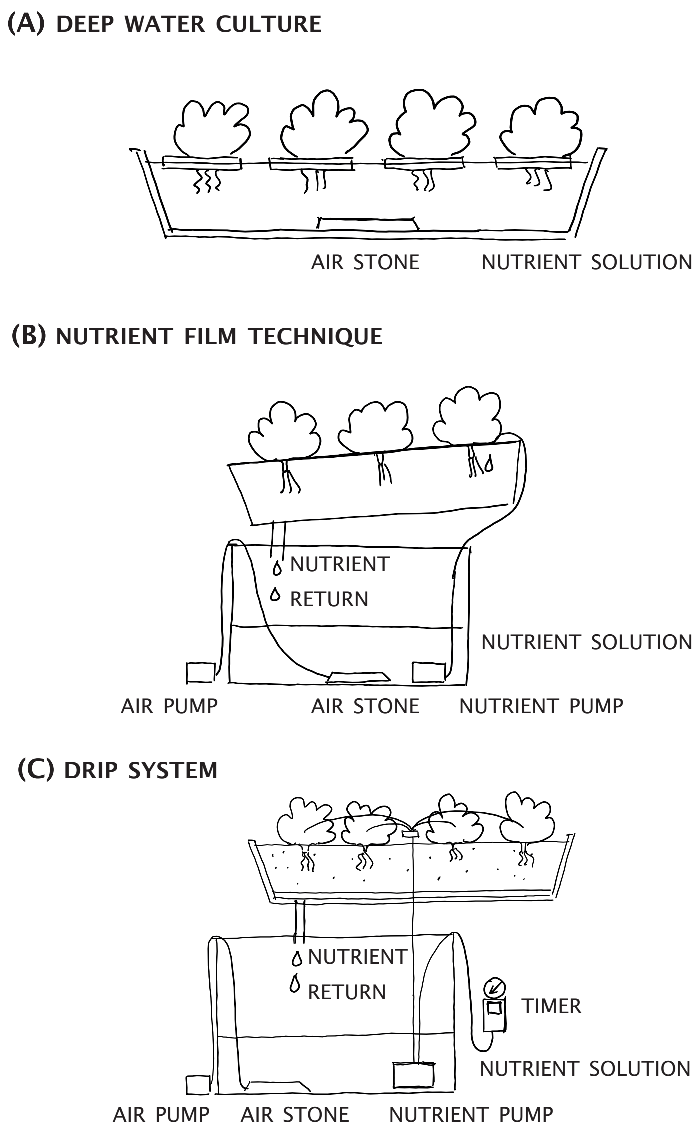

Figure 2.1: Types of hydroponic systems

fleece). Hydroponic systems can have very different scales — from massive commercial scale to domestic system replacing garden.

There are many types of hydroponic systems.

Deep water culture (Figure 2.1A) is a technique of growing plants with the roots immersed in water with polystyrene trays constituting mechanical support.

Nutrient Film Technique (NFT) (Figure 2.1B) is a method where the nutrient solution flows continuously through a channel moisturising plant roots.

In drip systems (Figure 2.1C) the nutrient solution is delivered to the root system of plants using drip irrigation. It is probably the most common technique used by commercial hydroponic farms, easy to operate on a large scale. Its relatively light weight and low infrastructure needs make it suitable for building integration.

Ebb and Flow is a method which grows plants in a substrate on big trays. A few times per day, the roots of plants are flooded with the nutrient solution. Because of the considerable weight of watering beds, Ebb and Flow is rarely integrated in the buildings.

The costs of hydroponic installation have to cover construction of the rooftop greenhouse (300 dollars/m^2 to 500 dollars/m^2 and growing equipment which vary depending on the variant. Relatively the cheapest option is NFT system. However, compared to a productive soil-based green roof, the installation is very expensive.

Example: Gotham Green

Gotham Green is a large-scale commercial hydroponic company in Chicago using NFT method. It owns four hydroponic greenhouses and some open-air farms. In 2015, they constructed the biggest urban rooftop hydroponic farm in the world atop a soap manufacturing plant Pullman with 7000 m^2 greenhouse. The building was designed by the sustainable design architecture office of William McDonough + Partners and has won many awards for design and innovation. It is also the world's first LEED-Platinum certified manufacturing plant in its industry, The costs of construction of a new Pullman greenhouse required an investment of over 7 million euros.

The high energy demand of the farm is partially covered by solar panels, passive ventilation design, and thermal curtains. Although normally greenhouses cannot absorb rainwater runoff, architects designed bioswales to slow and collect rainwater. All Gotham Greens facilities produce totally over 700 tons of greens and tomatoes per year. Gotham Greens supplies groceries and restaurants in Chicago and delivers products within a 100 km radius. The company is strictly commercial but supports various community programs (Puri and Komisar 2017).

2.2 Aquaponics

Aquaponics is a system that combines fish breeding with hydroponic plant cultivation in a closed loop. The characteristic feature of this ecosystem is an extremely efficient nutrient use. Plants use nutrients from fish excreta and uneaten feed. Coupling two systems together resolves the problem of organic matter that in conventional aquaculture accumulates at the bottom of the reservoir. There are three main types of aquaponics depending on the scale:

- Traditional one-loop system (Figure 2.2A) with the water freely recirculating between aquaculture and hydroponic units. The main flaw of the system is the necessity of trade-offs in terms of conditions for both subsystems which are not optimal for any of them.

- Decoupled (two-loop) system (Figure 2.2B) where the unit of aquaculture and hydroponics are separated. There is a one-way flow from the Recirculating aquaculture systems (RAS) to the hydroponic unit. In practice, the water that is supplied by RAS is equal to the amount of water transpired by plants. The water taken from the RAS is replaced by tap or rainwater. Because the rate of evapotranspiration of plants is slower than the assimilation of nutrients high amounts of additional nutrients are needed.

- Multi-loop system (Figure 2.2C) is the most complex variant of aquaponics. It includes the distillation/desalination loop allowing nutrient concentration in the water coming back to the fish tank to decrease and demineralisation loop allowing the pH of

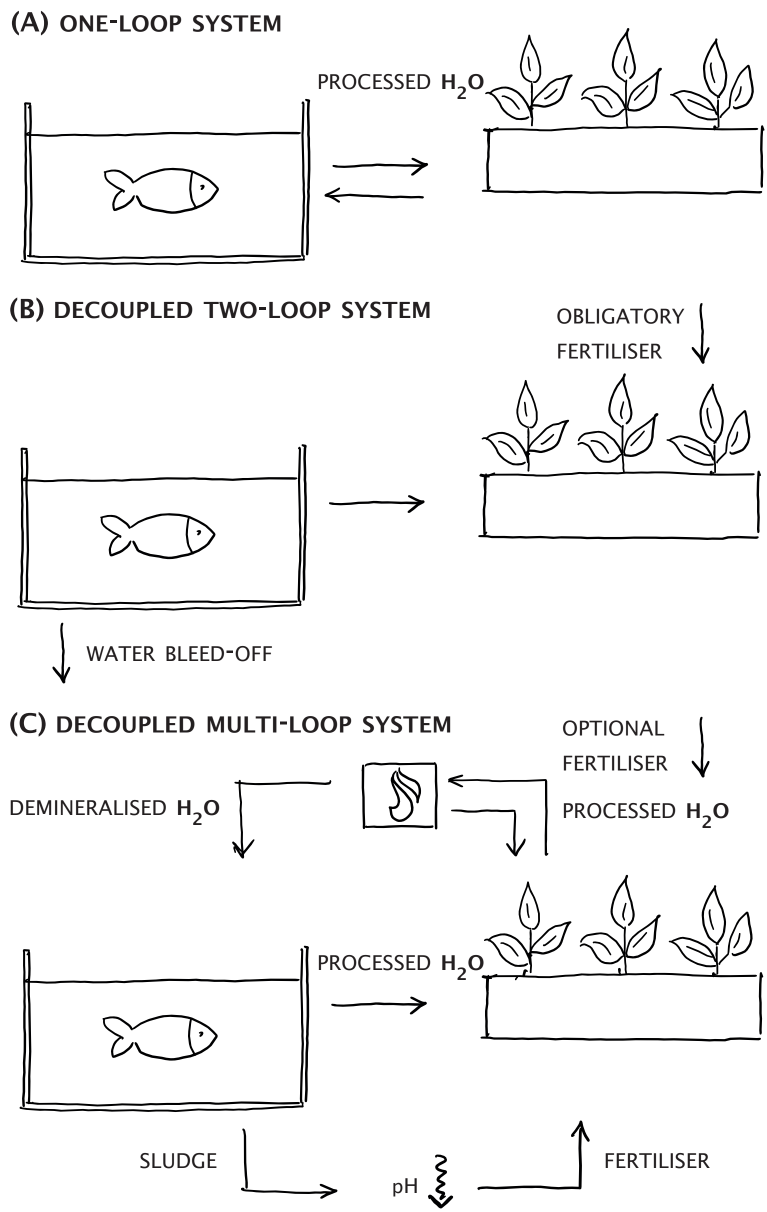

Figure 2.2: Types of aquaponic systems

the sludge from the fish tank to decrease. This system characterises by waste reduction in relation to the simple decoupled system and gives the best yields for both fish and plants (Goddek, Joyce, Wuertz, et al. 2019).

Example: BIGH

BIGH is an aquaponic company established in 2015 by Belgian architect Steven Beckers, a pioneer of cradle to cradle approach in architecture and urbanism. BIGH farms are examples of building-integrated aquaponics where a lot of attention is paid to the building synergies. The first and the biggest in Europe building-integrated aquaponic farm was built in 2016 in Brussels on the roof of an ancient slaughterhouse (Ferme Abbatoir). It consists of 2000 m^2 of high tech greenhouse and another 2000 m^2 productive outdoor garden. The site captures building energy loss, recycles rainwater and uses renewable solar energy [1]. Average fish production is 3000 per month [2]. To avoid significant environmental footprint, the maximum delivery distance is 12 km.

2.3 Aeroponics

Aeroponics is a method of growing plants in the air in a closed loop. The nutrients, water, and oxygen are supplied to the plants by misting the dangling roots. To keep the environment humidity, the system of sprayers, misters or foggers works periodically. There are two main types of aeroponics: horizontal one (Figure 2.3B) and vertical one in forms of columns (Figure 2.3A). Aeroponics is almost a disease-free cultivation due to the lack of any media that could spread the infections. As a result, the density of plants can be higher than in any other cultivation method. Another advantage is the abundance of oxygen in a root zone and access to the CO_2 concentrations ranging from 450 ppm to 780 ppm for photosynthesis.

[1] https://bigh.farm/

[2] https://www.rtbf.be/info/regions/detail_le-bar-de-bruxelles-un-poisson-produit-sur-le-toit-des-abattoirs-d-anderlecht?id=10082632

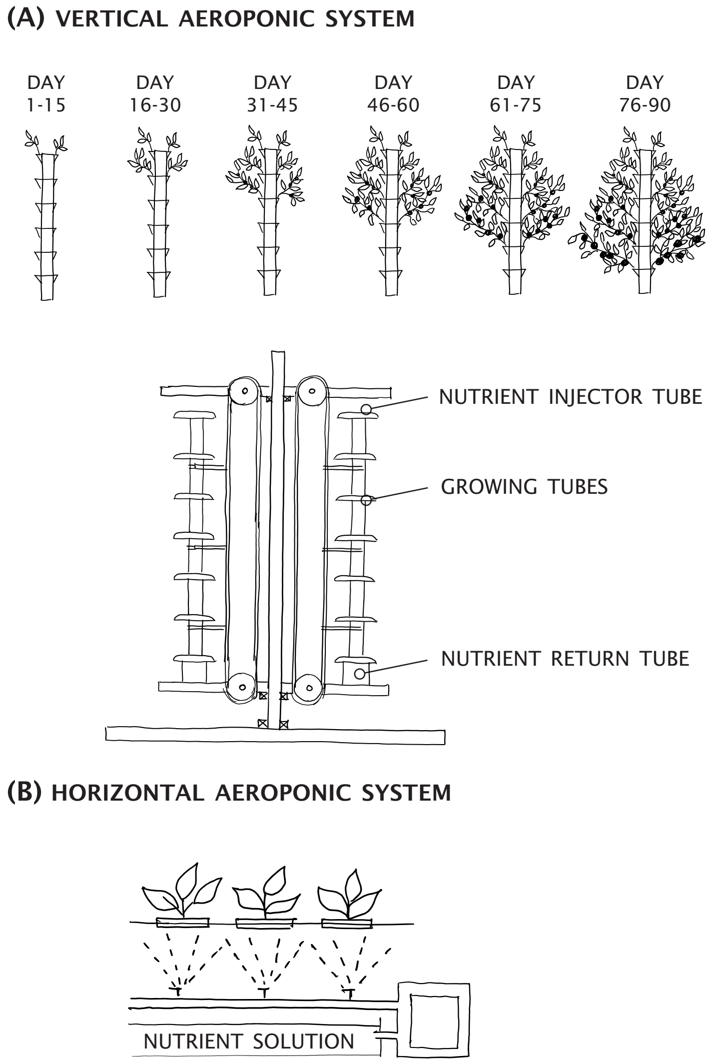

Figure 2.3: Types of aeroponic systems

Example: Agripolis

Agripolis is a company running open-air aeroponics in Paris. Operating from April to the end of October allows their farms to consume minimum energy (only for the pumps). The company uses in 30 % organic fertilisers. With several successful realisations to its credit, Agripolis is currently working on its major project that will be commissioned in 2020. The roof of Pavillon 6 du Parc des Expositions de Viparis with a surface of 14 000 m^2 will be the largest rooftop farm in the world. Besides the productive space, 500 m^2 will be destined for events and recreation. There will be also 140 plots available to rent for culture. The new project is expected to grow more than 30 different species, produce 1 t of fresh vegetables and fruit per day and employ 22 workers. The yields are going to supply the restaurant and private clients.

2.4 Soil-based farming

Soil-based rooftop farming is a method of growing vegetables and fruit on the top of buildings in the soil media. The earliest recorded rooftop agriculture project is the famous Hanging Gardens of Babylon which date back to 600 BCE. According to archeological studies these roof gardens were used to produce vegetables, fruit and possibly even fish! There are three types of soil-based farming: containers, raised beds and row farming.

Containers

Cultivation in containers (Figure 2.4A) demands the least of the initial input, is inexpensive, demands little labour and allows to rearrange the garden frequently. It is also the best option when the existing roof cannot sustain much load. The main problems include the susceptibility to moisture and heat loses. The plants demand regular watering but it is possible to install an automatic watering system. Besides, strong winds that rooftops often experience can topple containers. The best practice is to anchor containers together and put them against a higher building. Another disadvantage is that the soil cannot

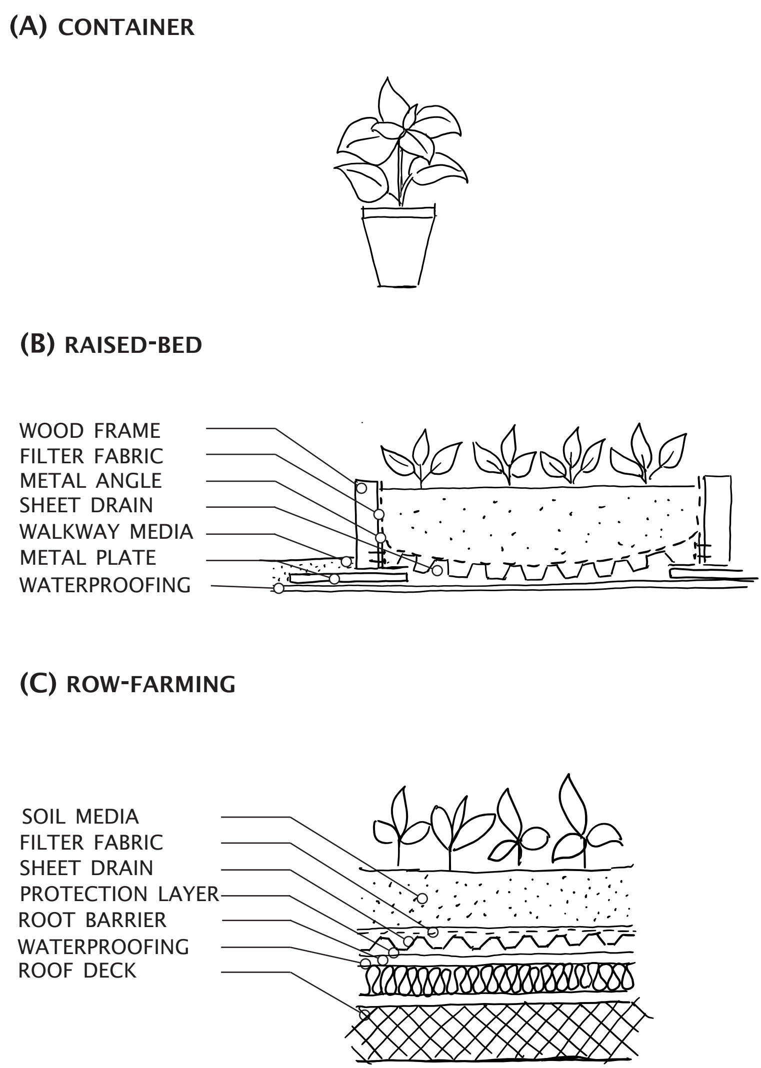

Figure 2.4: Types of soil-based systems

build over time. Container cultivation is in general not production-oriented but aims at increasing vegetation in urban areas. It is the most flexible way of plant cultivation within easy reach.

Raised beds

Growing food in raised beds (Figure 2.4B) gives higher yields and still demand low input. Therefore, raised beds are ideal for community gardens. Raised beds can be prefabricated low-profile structures filled with soil or built directly on site. They can be made entirely of an untreated wood (softwood is not durable enough and thus not recommended), have a steel framing or have a metal panelling. The drawback of untreated wood is that it deteriorates quickly and has to be replaced after 2 to four years. In the case of raised beds, the durability of the material is more important than in row farming, because the replacement is troublesome and expensive. Given the weights, the materials such as stone, brick or concrete are not suitable for rooftops. A very important aspect that prevents the beds from pooling water and exceeding weight limits is drainage. Bottomless raised beds are installed over a strong perforated layer — it can be a synthetic sheet drain or a perforated plastic pellets. The width of raised beds is standardised while the length is determined by the material dimensions and site layout. Most of them have a width of 120 cm to provide easy access from both sides or 90 cm if the access is from one side. The height varies according to structural limitations. As for the soil, the combinations and proportions are diverse but it is, in general, a mix of compost, pat moss, and vermiculture or perlite.

Row farming

Row farming (Figure 2.4C) is the most common method ideal for large scale production. The problem of unstable soil moisture or temperature is much smaller than in the containers. The growing beds' layout is flexible. To cultivate diverse vegetables and fruit directly in the soil the width of 45 cm is recommended but even with 35 cm the variety of species is already great (see section 5.5). The most important advantage is the lack of barriers to microbial activities and root spreading as well as unobstructed water flow. Other elements usually installed on the rooftop in the case of row farming are compost piles, tool and storage sheds, beehives and sometimes an observation platform. In the case of medium or large rooftops, an additional space off-site, e.g one floor below is very useful to wash and prepare the crops for the customers.

All above-mentioned methods are broadly used on rooftops which have become a platform of various initiatives strengthening local food production during the recent decade. They can be used also in the interiors but they demand much higher inputs. Soil-based farming and hydroponic systems are adaptable to the wall, too.

Example: Brooklyn Grange

The well known and widely documented example of a large commercial rooftop farm using the traditional row-farming method is Brooklyn Grange located in the heart of Queens in New York City. It is a privately owned for-profit company which started their activity in 2010. The architect of Brooklyn Grange is Jerry Caldari of Bromley Caldari Architects. Brooklyn Grange covers two rooftops of industrial buildings (4000 m^2) and owns also 30 beehives. The roof is made of 200 mm thick reinforced concrete, supported by a grid of "mushroom columns". Its bearing capacity allowed for the addition of 180 mm deep soil for planting. (Viljoen A. and Bohn K. 2014). As a result, growing beds are 20 cm to 30 cm deep and walkways of 2.5 cm. Brooklyn Grange applies organic growing methods although originally it was not the case. After two years of fertiliser use, they noticed that the soil fertility started to decline. They stopped and from that moment at the beginning of each season, the farm covers the beds with a layer of compost (23 m^3). The second strategy is growing nitrogen-fixing cover crops such as rye, buckwheat, vetch, and clover during the winter months. To keep the soil moisture the farm uses drip irrigation and covering with mulch. Besides, the rooftop has a capacity of absorbing runoff by 70 % to 85 %. Brooklyn Grange notes an annual yield of almost 10 t. Educational outreach is integral to the farm through a youth and adult program City Growers.

2.5 How to compare BIA methods?

Building-integrated architecture (BIA) interacts with the city in many different ways. Contrary to industrial agriculture, whose only function is food production, urban farming facilities usually are not and should not be monofunctional. In a dense and heterogeneous urban environment, it is the capability to respond to various needs that makes given solutions attractive and justifiable. It is important to look at different food production methods as a part of a complex network of different intensities and acting on a different scale.

To answer the title question *What form of food production integrated with the building?*, I grouped different criteria in three main aspects — each of them described in one chapter. Because at the centre of all our activities as architects is always a human, my first dimension was the social one. I decided to investigate the productivity (important in the context of rapid demographic growth), food quality (the basic factor influencing the health of society), impact on communities (with the abilities to respond to diverse social needs), and the human resources needed to maintain the systems.

The second area of my interest, vital for architects, was the spatial influence of integrating food production in the constructed environment. The three most important criteria were: adaptation to the existing structure, potential synergies between the building and plant growing unit, and the impact on urban space.

Finally, given that my work aims at identifying sustainable solutions, I included also an environmental perspective. It consists of: energy and water consumption (which are key resources for the future), CO_2 emissions (due to transport biodiversity enhancement in compensation for massive environmental destruction and hostility of urban space toward fauna and flora), chemicals use (with their destructive impact on the whole ecosystems), and limitations in terms of plants possible to grow with different methods.

My analysis of those three perspectives was conducted based on literature research. For each criterion and each method, I assigned a note from 1 to 5 where 1, depending on the criteria where 1 meant low, negative or bad, and 5, high, positive or good. Wherever possible, I compared the methods with industrial agriculture.

To present a bigger picture and balance my grades, I asked seven experts on agronomy and sustainable food production technologies for their evaluation of each criterion[3]. I obtained answers from different academic centres, among others: Iowa State University, Oxford India Centre for Sustainable Development, Queen's University in Belfast and AgroParisTech. Below each criterion description, I placed a table with my grade, median of experts score, and a small histogram of their responses.

The last chapter aims at presenting and comparing the results of our assessment for each method. Its objective is also to provide guidelines to architects and urban planners in the search for the most appropriate and sustainable solution. Wherever possible, I compared the methods with industrial agriculture.

[3]the survey results are available under: `https://github.com/annajuda/bia-methods-survey`

Chapter 3

Social impact

3.1 Productivity

Great majority of articles about alternative food production methods starts with a statement that in 2050 global population number is estimated at 9.5 billions, 70 % of which will live in urban areas [1]. This fact is usually followed by a statement that alternative ways of food production can successfully face the problem of a growing population. It is a simplification that makes people believe in the miracle solution of increased production which soilless methods can provide.

Currently, one-third of food produced globally (1.3 billion tonnes) gets lost or wasted. Despite the huge overproduction of food in the world, still, about 815 million people of the 7.6 billion people, or 10.7 %, suffer from chronic undernourishment [2]. Therefore, there is much more to do in terms of management in the food system than to produce more. Nonetheless, in fact, alternative food production methods are able to increase the potential of self-reliance of cities producing crops locally all year round. The factors of great importance are climatic conditions and vacant space.

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[1] www.un.org/development/desa/publications/world-population-prospects-the-2017-revision.html

[2] www.worldhunger.org/world-hunger-and-poverty-facts-and-statistics/

Potential to feed cities

The potential of urban agriculture to feed the cities is a debatable subject and there is no simple answer to this question, especially that it highly depends on the city itself and most notably on its geographical location. Sources quote different self-reliance potentials ranging 3 % to 100 % for three example cities: Cleveland, Bologna and Oakland (Table 3.1).

According to Minnich (1983), a plot 10 m by 10 m grown during an average 130 days of vegetation period can provide a household's yearly vegetable needs, including much of the household's nutritional requirements for vitamin's A, C, and B complex and iron. In urban conditions, covering 100 % of households' needs in such a way is unfeasible. However, a study from 2012 (S. S. Grewal and P. S. Grewal 2012) analysing the possibilities of food self-reliance proves that it might be the case in post-industrial cities in North America thanks to conditioned agriculture. According to the simulations, depending on the scenario, the City of Cleveland could meet even 100 % of its fresh produce need while using the hydroponic production and all available land and rooftop area. A more realistic scenario predicts that using conventional urban gardening only on vacant lots the city could attain 22 % of self-reliance.

By comparison, the example of Bologna shows the city could produce 77 % of fresh vegetable and fruit demand using all vacant lots and available rooftops with different techniques (Orsini, Gasperi, and Marchetti 2014). It should be taken into account that the city is a representative case study of Mediterranean cities and has advantageous climatic conditions with a long vegetative period.

The assessment of potential in Oakland revealed that under the most realistic scenario, depending on the growing method, 3 % to 7 % of current consumption could be obtained. The simulations included vacant lots as well as building integrated farming. Using of 202 ha of vacant urban space for farming could provide from 14 % to 36 % of demand. This study did not consider conditioned growing methods. The research emphasised the fact that the current diet of the city's inhabitants constituted only 21 % of the recommended amount of fresh produce consumption. For that reason, a set of simulations for increased demand has been run. The results showed that urban agri-

	Cleveland	Bologna	Oakland
population	431 363	386 298	390 724
vacant space	1381 ha	82 ha	40.4 ha to 200 ha
methods	soil-based, hydroponics	varied	soil-based (varied intensity)
self-reliance	22 % to 100 %	77 %	3 % to 36 %

Table 3.1: Potential self-reliance of Cleveland, Bologna and Oakland depending on the scenario

culture could provide only 1 % to 7.7 % of recommended fresh produce (with high land use (McClintock, Cooper, and Khandeshi 2013)).

Estimation of productivity of each method

Estimated productivity in the case of lettuce in standard hydroponics or substrate culture varies between 6.0 kg/m^2 and 6.52 kg/m^2 depending on the research (Lennard 2005). The results for aquaponics are slightly lower: 5.7 kg/m^2 of lettuce production for high fish density and 5.6 kg/m^2 in lettuce production for low fish density (Pantanella et al. 2010).

The student study made on a CombaGroup in Yverdon-les-Bains in Switzerland revealed that aeroponics performs the best with its 64 kg/m^2 to 70 kg/m^2 (Bonzi and Vuadens 2019). In Brooklyn Grange total lettuce production per year adds up to 4.8 kg/m^2 (Goldstein et al. 2016). By comparison, conventional agriculture produces in average 3.9 kg/m^2 although it is strongly case dependent (Barbosa et al. 2015).

Yields obtained with all soilless methods significantly outperform traditional soil-based production not only due to a dense disposition of plants per m^2 and faster and vigorous plant growth but also their all-year-round production in conditioned environment (Rodríguez-Delfín et al. 2017). Besides in aquaponics, the production of, for instance, tilapia averages 560 kg/m^3 year (Rakocy et al. 2010).

The experts were asked to evaluate the "Productivity" in the scale from 1 (very low) to 5 (very high). The median and histogram of their responses compared to my score based on the literature study is in the Table 3.2. The experts were unanimous that soilless methods were more productive than soil-based one. However, they underestimated aeroponics productivity which, in reality, outperforms hydroponics. Soil-based and conventional methods were rated as moderate, but in comparison to impressive yields of alternative methods, they perform poorly.

	kg/m^{2}year	my score	expert score	histogram
Hydroponics	41	4	4	
Aquaponics	37	4	4	
Aeroponics	64	5	4	
Soil-based	5	2	3	
Conventional	4	2	3	

Table 3.2: Productivity of food production methods: expected production volume of lettuce in kg per m^2 of installation per year; author's score of productivity based on literature study, median of expert scores from conducted survey and histogram of expert scores.

3.2 Food quality

A long-held tenet is that "healthy soils" will produce healthy and nutritious food that in turn will ensure healthy human beings and animals (Hornick 1992). Only recent studies have confirmed the extent to which nutrient content is the result of complex conditions of plant cultures. Among the factors influencing the nutritional value of plants are soil pH, available nutrients, texture, organic matter content and soil-water relationships, weather and climatic factors, including temperature, rainfall, and light intensity, cultural practices, postharvest handling and storage, and fertiliser applications. A very important factor is also letting the fruit achieve maturity. According to a study from 1987, apricots and apples harvested green contained no ascorbic acid while fully ripe fruit contained 60 mg per 100 g. Except for seasonal products from local market stands, the majority of vegetables and fruit that we buy are picked green to withstand transport.

Hydroponic and aquaponic companies very often use this argument to promote their local products. For example, in Agripolis the delivery never exceeds 12 hours from the harvest which is a guarantee of ripe and fresh products. Nevertheless, the quality of soilless food is a controversial subject. Many sources, obviously with hydroponics producers at the forefront, say that the nutritional value of plants grown alternatively is the same or higher than its soil-grown counterpart. Unfortunately, scientific research does not dispel doubts. A study from 2015 which compared the nutrient content of strawberries and raspberries grown hydroponically and traditionally showed that the "healthy" anti-oxidant compounds (e.g. vitamin C, tocopherol and total polyphenolic compounds) were significantly higher in hydroponically grown strawberries compared to the soil-grown ones but the opposite was true for raspberries (Treftz, Zhang, and Omaye 2015). Another study from 1998 revealed that tomatoes grown in organic soil (100 % or 50 % of vermicompost) were richer in nutrients that in hydroponics (Premuzic et al. 1998) while the research from 2013 showed the lettuce in soilless conditions contained more vitamin C than in the soil (Buchanan and Omaye 2013). The main problem with those research credibility is not only different soil control samples but also the lack of description of its quality (except the tomatoes). The key to high-quality products are healthy soils with teeming bacterial life and full mineral availability. The micro-organisms in the soil are the crucial factor that makes minerals available for plants. Intuitively, lack of soil could lead to a poorer nutrient content but there is no scientific evidence to justify this objection.

Besides, opponents of hydroponic products refer to very poor Brix value (a combination of sugar, amino acids, oils, proteins, flavonoids, and minerals) of those products which can easily be measured by refractometer. This is apparent in the tendency of vegetables and fruit to rot, but also in the lack of taste.

There is also doubt about the impact of the sterility of plants produced in aeroponics and hydroponics. Both technologies grow plants in a sterile environment and produce sterile plants. Given that humans are not sterile at all, the question about the consequences for our immune system is open.

As for aquaponics, the situation is different. Although the plants grow also in the water, there are no synthetic fertilisers and the presence of fish makes the water in the cycle much richer — and so the products.

The easiest option to ensure product quality seems to be a soil-based method. The examples of rooftop farms confirm the trend of using organic methods, close to permaculture practices, ensuring healthy soil and fertility maintenance. Since such farms cannot compete in terms of quantity with conventional agriculture, they choose to compete, with success, in terms of quality.

	my score	expert score	histogram
Hydroponics	3	3	
Aquaponics	3	3	
Aeroponics	3	3	
Soil-based	4	3	
Conventional	2	4	

Table 3.3: Food quality of food production methods; author's score of productivity based on literature study, median of expert scores from conducted survey and histogram of expert scores.

Given all those facts, soilless culture prevalence over conventional agriculture does not lie in what it has but in what it has not. Food produced alternatively lacks pesticides and herbicides present in fruit and vegetables bought in the markets. There is also no risk of contamination — the problem that increasingly touches soil products. Besides, no chemicals preventing vegetables over ripening in transit are necessary due to local production. At the same time, a more credible scientific study evaluating the quality of vegetables and fruit has to be done.

The experts were asked to evaluate "Food quality" in scale from 1 (very low) to 5 (very high). The median and histogram of their responses compared to my score based on the literature study is in the Table 3.3. The main difference between my evaluation and experts' one, concerns soil-based and conventional methods. Based on the examples of existing rooftop farms, we see that soil-based farming provides produce of better quality following organic practices and using no chemicals. As for industrial agriculture, fruit and vegetables are peppered with chemicals (see and often originate from over-exploited soil.

3.3 Impact on communities

A wide range of motivations may lie behind rooftop agriculture ranging from bringing a neighbourhood together through a productive garden, generating an income for a community or increasing food security for a financially challenged family. Besides, some rooftop gardens are open to visitors for different reasons: using a volunteer workforce, receiving students and children providing a green space for customers of a restaurant or shop in the building. There is a huge variety of social profiles that a building integrated unit can have to boost different aspects of community life. There can be community gardens, health-focused gardens, showcase gardens, residents' amenities gardens, school gardens, university gardens, etc. The analysis of different examples of various rooftop agriculture (soil-based, hydroponics, aquaponics, and aeroponics) demonstrated that the social impact very often constituted the main impulse of the project. According to the study analysing 57 different rooftop farms around the world, 19 % intended directly for education and social function, 39 % of them aimed at life quality improvement and 26 % were commercial. Other main objectives were innovation and image (Buehler and Junge 2016).

Rooftop agriculture can influence the communities in different ways and boost the following aspects: education, research, general well-being, social inclusion, waste management.

Empowering communities

A very positive emerging trend that we can observe recently is the inclusion of rooftop gardens on newly constructed residential buildings to arrange a meeting place and bring the neighbourhood together and promote a sense of community by common activities and responsibility.

Education

Many urban farms highlight the fact that education is their main objective right after food production. In the first place, it considers school and university roofs that present a wide range of food production types ranging from very simple forms to larger showcase projects to compensate for the lack of school yard. The example can be Toronto, where five non- profit organisations fixed the objective of creating a productive garden in every school to teach students practical skills related to the market garden such as growing, harvesting, cooking and marketing the food. One of the schools installed a garden on its roof of 1000 m^2, initially destined to a tennis court what enabled it to easily meet structure capacity requirements. The techniques chosen in the majority of cases in Toronto were soil-filled containers[3].

The educative profile concerns not only the schools and universities. Many farms aim at reaching out to the wider public: individuals and associations. For example, the main mission of the Rotterdam Environment Center with its soil-based garden of 1000 m^2 is to teach about healthy food and urban agriculture through a variety of educational programs. At the same time, vegetables and fruit produced by the farm are served in the rooftop restaurant and sold weekly on the rooftop market[4].

Research

Among research-oriented examples, we can mention an experimental hydroponic greenhouse on top of a shipping container, with fish tanks

[3] `https://www.thestar.com/yourtoronto/education/2013/12/25/eastdale_collegiate_opens_its_roof_to_urban_agriculture.html`

[4] `www.schieblock.com/semi-publieke-ruimtes#schieblock-dakakker`

and the recirculation system established by ECF in Berlin in 2012 or a rooftop garden arranged in the same year in Paris atop a historic building of AgroParisTech, the country's leading agriculture school. The latter concentrates the research on different substrates, variability in growing conditions, pollution levels, and productivity [5].

Psychological and physical benefits

Greenery, or more precisely horticultural therapy, is known for ages and supports recovery, both physical and mental. It is no wonder that therapeutic rooftop gardens exist atop hospitals in Seoul, Toledo, Ohio as well as other health facilities such as the rooftop of The Municipal Institute for People with Disabilities in Barcelona. The latter includes a multi-functional garden providing a safe environment for recreation, learning, and social interaction for these vulnerable groups as well as giving the possibility to actively contribute to the maintenance of the site. The project has met great success in the social empowering of people with disabilities[6].

Gardening is an outdoor activity that allows reaching a high level of satisfaction from obtaining yields, beautifying the space, giving the feeling of peace and releasing stress. The relationship between gardening and the perceptions of life satisfaction was the subject of study of Waliczek, Zajicek, and Lineberger (2005). The results showed that energy level, optimism, zest for life and physical activity level were significantly higher among the group of gardeners.

Leake, Adam-Bradford, and Rigby (2009) concluded that together with physical activities associated with "grow-your-own" the health benefits are likely to outweigh risks at most sites that exceed current soil guideline values.

Social inclusion

A frequent objection to urban farming is a little poverty alleviation impact(Hampwaye 2013). Organic food grew in cities is often more

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[5] www.topager.com/portfolio-item/potager-sur-le-toit-d-agroparistech/

[6] www.naturvation.eu/blog/20180613/exploring-rooftop-gardens-barcelona

expensive than the produce from the market. Besides, in developed countries urban farms cooperate directly with local shops, restaurants, and other facilities inaccessible to the poorest members of the society. Thus, unless the project aims directly at the poorest, it does not affect food access equality improvement. In developed countries, there are only a few examples of this kind. For instance, a farm atop a new building in the disadvantaged South Side of Chicago is targeted specifically at socially excluded and the poorest members of the society. Gardening is a way of preparing young people in a difficult situation for their future independent life[7].

In developing countries, social inclusion motivates a significant part of projects. In 2014 in Cairo, a great initiative supporting poor families living in the buildings with easy access to the roof was started. The Participatory Development Programme financed 15 simple hydroponic installations, delivering training and help throughout the whole crop cycle to the participants. Self-growing food allowed the whole families to enrich a diet which otherwise was very low-nutritious because of prohibitive prices of fresh vegetables and fruit. The surplus sold in the local market provided additional income to the families (Sarant 2015).

Another interesting project was initiated in the Gaza Strip which suffers, among other things, from the limited access to steady sources of water. In 2013 FAO installed there simple aquaponic systems in poor, food insecure and predominantly female-headed households. Despite initial success, this project did not manage to bring long term results as after the pilot period with expert assistance, many households did not have means to buy necessary inputs such as seeds and fish feed[8]. However, it demonstrated that, if properly run, such a project had the potential of changing life conditions. Also, the study carried out in four cities in Zambia revealed that, except for the capital city Lusaka, during the consumption period estimated to 4 months, the urban agriculture contribution in annual household income ranged from 48 % to 53 % (Hampwaye 2013).

[7] www.garycomeryouthcenter.org/about/gcyc_building

[8] www.fao.org/3/a-i5620e.pdf

Positive shift in terms of waste

It is estimated that 25 % of the world's food calories and up to 50 % of total food weight are lost or wasted before they are consumed[9]. Given that the food at the end of the food supply chain has accumulated already a significant footprint, it is the most painful food waste. The reason for such a loss in developing countries is inappropriate transport or storage. In developed countries, food-wasting happens usually in our homes, restaurants or supermarkets. Urban farming in both cases has a potential for positive change: in the first case by transport and storage reduction and the second one by sensitisation. The consumerism of our world does not teach us respect for the products we obtain. As an adage says, "out of sight, out of mind". This proverb works inversely, too. The impact of urban farming on the waste problem is immeasurable but it can be significant especially in the case of children. Tackling waste problem is considered one of the most effective ways of boosting food availability globally.

Overall impact on communities

The greatest social impact on communities is observed for soil-based rooftops which are platforms for many building communities activities. Their main advantage over other technologies lies in its universal application and the greatest social trust they enjoy. Working with the soil offers health benefits and a sense of connection with nature in a primal way, as opposed to the hi-tech methods. Soilless cultures are more frequently commercial and hence, less willing to leave non-productive spaces for other purposes. However, they are in line with local needs and sometimes fulfil some supplementary functions. Application of simplified versions of hydroponics and aquaponics can have a huge positive impact in developing countries but demands regular supervision and high financial input.

The experts were asked to evaluate "Overall impact on communities" in scale from 1 (very negative) to 5 (very positive). The median and histogram of their responses compared to my score based on the literature study is in the Table 3.4. Contrary to experts' evaluation, I found that soilless technologies have the potential to positively affect

[9] `www.nationalgeographic.com/foodfeatures/feeding-9-billion/`

communities, especially in terms of education and social inclusion. I was also more enthusiastic about the positive influence of soil-based method which concerns all mentioned above kinds of impact. In my opinion, conventional agriculture is neutral in terms of communities since I did not find any example of a positive impact.

	my score	expert score	histogram
Hydroponics	4	3	
Aquaponics	4	3	
Aeroponics	4	3	
Soil-based	5	4	
Conventional	3	4	

Table 3.4: Impact on communities of food production methods; author's score based on literature study, median of expert scores from conducted survey and histogram of expert scores.

3.4 Human resources

Soil-less methods of food production require highly specialised personnel. Temperature, humidity, air circulation, and light have to be carefully monitored and well-calibrated and nutrient output regularly controlled. Even the simplest home aquaponic or hydroponic systems need regular control at least twice a day and the specific knowledge to maintain the system. The advocates of alternative methods state that all skills required for maintenance of, for example, the aeroponic system are possible to acquire within a few months, contrary to extended knowledge needed in conventional agriculture.

Taking lessons from, already mentioned above, the case of the Gaza Strip, the success of social projects involving soilless methods demands not only a good training of participants but also constant technical support for them. The need for qualified personnel is, together with high costs, a major obstacle to the widespread use of these techniques in simplified form in developing countries. Although the level of complexion is usually claimed to be a disadvantage, it has a positive side because of the creation of jobs which are often in line with the level of qualification in the city.

Among all soilless technologies, the most complex is obviously aquaponics because it requires the competences both about fish breeding and plant growing. As far as row-farming is concerned, maintaining the soil fertility demand quite a high labour input, beyond the knowledge. Besides, in the case of medium and large scale projects, an urban farmer needs to be very versatile and skilful in marketing, social events organisation, and is considered a face of the farm. By comparison, the level of mechanisation in conventional agriculture is going through a great deal of change and in modern farms, it frequently comes down to monitoring and thus reduced need for labour.

	my score	expert score	histogram
Hydroponics	3	3	
Aquaponics	4	3	
Aeroponics	3	3	
Soil-based	5	2	
Conventional	2	3	

Table 3.5: Amount of human resources needed for food production methods; author's score of productivity based on literature study, median of expert scores from conducted survey and histogram of expert scores.

The experts were asked to evaluate "Amount of human resources needed" in scale from 1 (very low) to 5 (very high). The median and histogram of their responses compared to my score based on the literature study is in the Table 3.5. Contrary to experts' evaluation, I evaluate soil-base technologies very labour-demanding. Besides, aquaponics as a more sophisticated system, demands more skills and control than hydroponics and aeroponics.

Chapter 4

Spacial impact

4.1 Adaptation to existing structure

Using a rooftop for any of the four analysed methods is the most frequent way of integrating food production in the building. Blind walls can also be used for culture but the structure for such a unit is rather independent. The main requirement in this regard is a necessary space. In the case of rooftops, many aspects have to be taken into consideration while integrating into an existing structure.

Accessibility

Regardless of the technology, the rooftop has to be accessible. Given the intensive flow of equipment, resources and then crops the most comfortable is always access by lift. Very important is also access to the roof at the phase of construction. The soil and construction materials are usually lifted onto the roof using a mobile crane. Another aspect is access to the roof out of "office hours" of the building which has to be provided. Furthermore, the rooftop has to meet exit regulations from fire code. In the case of aquaponics, it is even more complicated because the operations require additional infrastructure to access the roof and meet requirements of proper emergency exit and fire regulations (Proksch, Ianchenko, and Kotzen 2019). Change of the roof function from inaccessible to accessible is also possible but more costly since it includes the construction works. Rooftop access always has to meet local building code requirements.

Structure capacity

To be sure that the construction will bear new charges, the structural capacity of the roof has to be always verified by a structural engineer. Only 30 cm of the soil weights approximately 410 kg/m^2. In principle, the most convenient rooftops for farming in terms of loads are on existing concrete deck industrial buildings or on a new building designed in a way to support the charges (Mandel 2013). At the same time, concrete structure poured on-site and hence depends on the workmanship and is difficult to assess in terms of additional bearing capacity (Gorgolewski and Straka 2017). Sanyé-Mengual, Martinez-Blanco, et al. (2018) proved also that retail parks roofs easily accomplish requirements and that 53 % to 98 % of them are technically and economically feasible to accommodate a rooftop greenhouse and in many cases are of much bigger potential that industrial zones.

Since the roof is in general never equally strong on the whole surface, the distribution of different elements on the roof is of importance and should also be consulted with an expert to prevent structural damages. Heavier elements such as raised beds should be placed directly above the columns or load-bearing walls. Structurally weaker parts can be used to harness the solar energy with an array of solar panels. Other functional amenities that can be located with consideration of the bearing capacity are compost pile, tool shed apiary, henhouse or nursery.

The weight of water is the biggest obstacle for rooftop aquaponics systems. To minimize the charges, lightweight water distribution systems such as Nutrient Film Technique or media-based growing are prioritised rather than deep water culture. Fish tanks are located on the level below the crop growing which is possible due to decreased light demand (Proksch, Ianchenko, and Kotzen 2019).

Open-air aeroponics is a technique that demands the lightest equipment. According to Agripolis, even the roofs with low bearing capacity can arrange a food production unit without any construction works[1].

[1] `http://agripolis.eu/non-classe/communique-bientot-a-paris-la-plus-grande-ferme-urbaine-en-toiture-au-monde/`

The company installs the farms on the roof with a minimum bearing capacity of 150 kg/m^2. It is important to choose an appropriate food production method since the cost of structural changes in the existing building is much higher than when it is considered right from the start.

Waterproofing

Installing a soil-based food production unit needs to be preceded by the specialistic control of water tightness. For row-farming it has to be in excellent condition, typically no older than 5 years. If needed, the waterproofing layer has to be patched, added or replaced[2]. The latter ensures maximum protection. In many building codes, only 2 layers of waterproofing are allowed. If the second one is damaged, the whole layer has to be replaced (Mandel 2013). Almost any type of waterproofing membrane is convenient but some of them need additional plastic root barriers to avoid the damages. According to FLL Guideline testing which sets international standards in the green roof technology, the most durable is PVC[2]. In some cases, thermal insulation is also located on top of the waterproof layer providing further protection from roots. Soilless methods do not require the excellent conditions of waterproofing.

Sun exposure

Looking for a suitable place for row-farming or soilless food production farms requires a proper orientation preferably from the south. When installing a greenhouse, east to west orientation (E–W) is preferable over north to south orientation (N–S) (Montero et al. 2017). It is very important that in a conditioned environment, the plants receive as much sunlight as possible. Neighbourhood buildings should not be much taller than the rooftop to not to shade the roof but a vacant lot on the south is also unfavourable — in case of construction, the farm can lose the sun exposure. Another unfavourable site is next to the reflective facade of neighbouring building. The reflected light can

[2] `www.greenrooftechnology.com/green-roofs-explained#grow-food-green-roof`

literally burn some varieties of plants. Temperature fluctuations can cause crops to bolt prematurely (Mandel 2013).

Wind

The higher the green rooftop, the stronger the winds are. Since strong winds can cause winnowing (soil loss) and desiccation (soil drying), it is always better to stay a bit lower. A higher neighbouring building from the north can be a precious ally and act as a windbreak. Installing wind screening is a popular practice. A problem of strong winds concerns also greenhouses. Compared to their ground-level counterparts, rooftop greenhouses are much more engineered structures, designed to withstand snow loads and strong winds. Sealing the joint between the greenhouse and the roof deck is crucial to prevent the wind from blowing from underneath and shaking the structure. Such storm safe high tech greenhouses, called Venlo greenhouses, are frequently very expensive due to required building code compliance (Mandel 2013).

Security

In the case of change of the function from inaccessible to the accessible roof, the security has to be guaranteed by means of railing and barriers. Railing system has to meet local building code requirements. According to Swiss building code requirements, any accessible surface and with a drop height of at least 100 cm must be secured by protection elements[3].

Water access

At least one point of connection is necessary to provide watering for plants. The second point is very precious in the case of medium and large farms. The farm can be connected to a municipal water supply or a cistern with rainwater in the basement if it is large enough and the pump allows to reach the roof. In case of the lack of water

[3] `www.suissetec.ch/files/PDFs/Merkblaetter/Spengler/Franz/2017_NT_Garde-corps_sur_toits_plats.pdf`

tap, rainwater barrel can also be installed on the roof but due to its significant weight, it has to be confirmed by an engineer.

Land use and customers proximity

In the case of commercial rooftop farms, it is important to check if agriculture is permitted in the relevant land use zone and ensure that all the customers are in the proximity. The ideal situation is when the farm completes the functions already existing in the building so that no transport across the city is needed.

Overall adaptation to existing structure

The experts were asked to evaluate "Adaptation to existing structure" in scale from 1 (very low) to 5 (very high). The median and histogram of their responses compared to my score based on the literature study is in the Table 4.1.

	my score	expert score	histogram
Hydroponics	3	3	
Aquaponics	1	3	
Aeroponics	4	3	
Soil-based	3	3	

Table 4.1: Adaptation to existing structure of food production methods; author's score based on literature study, median of expert scores from conducted survey and histogram of expert scores.

The main difference in easiness of adaptation to existing structure lies in the bearing capacity of the roof and watertightness. All the rest aspects do not do not vary considerably depending on the method. Aeroponics which is the lightest and does not require watertighness works, received the highest note from my grades but its advantages were noted by few experts. Conversely, aquaponics which is a heavy system, demanding special spatial configuration (two storeys), got my lowest note. The histogram does not show any variations in experts' evaluation of this method.

4.2 Building synergies

Due to the possible synergies, building-integrated food production in an urban context can be very interesting for architects and urban planners.

Reduction of energy consumption of the building

The roof covered with vegetation stands out by its significant thermal efficiency. While the surface of the roof exposed to the sun can reach the temperature between 65 °C to 110 °C (zinc) depending on the material, the same roof covered with vegetation keeps the exterior temperature. That has a huge impact on the interior temperature and the need for cooling. In the winter the heat losses are also slightly reduced but as a wet soil does not have good insulation characteristics, these advantages are very often overestimated (Gorgolewski and Straka 2017). Therefore, it is not surprising that some projects have originated just from the need to reduce the temperature in the building. The example can be the Changi General Hospital in Singapore which uses simple hydroponics to grow tomatoes and herbs for hospital use (Geoff Wilson 2005).

Very interesting from the energy consumption point of view is the synergy between the building and the greenhouses atop the roof. It is an innovative concept which increases the efficiency the resource use and enhances the sustainability of both systems. As a result, the comfort in the building is increased with lower energy input and the crops in an urban context can be produced. Greenhouses can take advantage of the residual energy from the building to heat the growing space in cold months. Conversely, in the spring the greenhouse can act as a solar collector and spare heat generated inside can be used to heat the building. In hot periods, the airflow from the building can help the ventilation of the greenhouse (Montero et al. 2017). According to a theoretical analysis of energy flow based on an office building in the Mediterranean area, the demand for heating during a winter day was reduced by 79 % (Sanyé-Mengual, Martinez-Blanco, et al. 2018). Recent studies show also that due to the thermal inertia of construction materials the night-time temperature decay in winter is 10 °C lower in building-integrated greenhouses than in conventional ones (Pons et al. 2015). Moreover, the crop productivity was higher in heated, in such way, greenhouses when compared to conventional unheated greenhouse tomato production in the same area.

As a result of energy synergies, hydroponic greenhouses use less energy than their ground-level counterparts. Installing an air recirculation system between the greenhouse and the building, designers should be aware that daily airborne pollen and fungi concentrations originating from the greenhouse are the major components of airborne biological contaminants. Indoor temperature and relative humidity are in strong correlation in fungi spores development. To prevent the contaminants from spreading in the whole building, the application of preventive solutions such as the implementation of appropriate filters in ventilation air ducts or a system able to interrupt during critical periods has to be applied (Ercilla-Montserrat et al. 2017).

CO_2 flow

In conventional greenhouses, the injection of CO_2 is a common practice supporting the photosynthesis. Integration of the greenhouse in the building enables taking advantage of the CO_2 already present in exhaust air from the building. It is a carbon source free of environmental and economical costs (Pons et al. 2015).

Reduced water consumption

Water in many places is already a scarce resource, and due to groundwater depletion and contamination, the problem will shortly concern more regions. At the same time, agricultural production accounts for 92 % of global freshwater use, while industrial production uses 4.4 %, and domestic water only 3.6 % of the total consumption (Hoekstra and Mekonnen 2012). In such a perspective, it is important to develop agricultural techniques with low water input requirements and to improve water management through better reuse.

The easiest way to economise water is rainwater harvest. Bill Mollison, father of permaculture emphasises that "if you only do one thing, collect rainwater". This solution is relatively low-cost and low-tech. Rainwater tanks can be located on the roof or at a ground level. Even 90 % of plants' demand for water can be covered with rainwater from the rainwater harvesting system in the building. The wastewater from irrigation can be reused in the building for flushing the toilets which quite shockingly correspond currently to even 90 % of drinking water demand in the building (Delmás 2017).

Another possibility is a decentralised greywater treatment system to reuse water in a circulating system for watering. This solution is more and more present in ecological architecture. Maison Productive House in Canada is an example of both rainwater and greywater use for irrigation.

An extreme version, considered already very seriously in water-scarce places is purifying black water into drinking water and keeping it in a closed-loop. This technology is under development[4]. Blackwater treatment can play an important role in food production. A recent study funded by the German Federal Ministry of Education and Research within the framework of the project Roof Water-Farm proved that black water can be reused as a liquid fertiliser for hydroponic or aquaponic systems. A process of its production, including hydrolysis, sedimentation, microfiltration, nanofiltration, hygienisation (bacteria and viruses elimination), is quite complex (Gehrke 2014) but takes advantage of waste. Hence, the mission of Roof Water-Farm, an experimental unit in Berlin, is to investigate the opportunities for building-integrated water treatment systems to irrigate and fertilise roof-top greenhouses[5].

On one hand, food production in the city increases the demand for water, but on the other hand, when well-designed, water consumption can be very efficient and beneficial both for the building and the food production unit.

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[4]`https://ideas.ted.com/would-you-drink-desalinated-seawater-recycled-sewage-water-get-ready-to-find-out/`

[5]`www.roofwaterfarm.com/`

Soundproofing

The soil is one of the best material protecting against the noise. Only 12 cm of the soil covered with vegetation can reduce the aerial noise by 40 dB in the radius of 8 m in the interior of the building (Baumann and Peiger 2018).

Protection of watertightness

The destruction of the layer of water tightness is mainly due to heat. Vegetation keeps it out of UV radiation. Besides, vegetation constitutes a barrier against bad weather (Baumann and Peiger 2018). Those 2 aspects increase significantly lifespan of the layer of water-tightness. According to FLL Guideline, a properly installed and maintained green roof can extend the lifespan of the roof even 2–3 times (up to 60 years)[6].

Overall potential of building synergies

The synergies in building-integrated food production is still an innovative field which is being researched. Ideally, the synergies should be achieved in terms of energy, water, and gaseous flows. Energy and gaseous flows synergies can be achieved only in the case of conditioned plant growing units.

However, for the time being, there are very few projects that well integrate food production in the building metabolism. A good example is the ICTA-ICP Lab which is an experimental, research-oriented site in Universitat Autònoma de Barcelona (UAB) consisting of two greenhouses with soil-less production. The project, which started in 2014, integrates the energy, water, and CO_2 flows in the building. The water used in the cycle is collected on the rooftop (Pons et al. 2015).

The experts were asked to evaluate “Benefits from building synergies” in scale from 1 (very low) to 5 (very high). The median and histogram of their responses compared to my score based on the literature study is in the Table 4.2. Potential synergies are possible regardless of the soilless method if the system is conditioned.

[6] www.greenrooftechnology.com/green-roofs-explained#grow-food-green-roof

	my score	expert score	histogram
Hydroponics (conditioned)	4	3	
Aquaponics (conditioned)	4	4	
Aeroponics (conditioned)	4	3	
Soil-based	4	3	

Table 4.2: Benefits from building synergies for food production methods; author's score based on literature study, median of expert scores from conducted survey and histogram of expert scores.

4.3 Impact on urban space

The urban space benefits from green rooftops in many ways: some green recreational areas can emerge, run-off is delayed, heat urban island is reduced, air quality is improved and organic waste is recycled.

More green spaces

Many farms beside their food production objectives provide some recreational spaces for residents. It can be outdoor space open for public use or a site proposing organised activities for residents. In both cases, such a space constitutes a great alternative to spend time within the perimeter of the city and raises the aesthetics of urban surroundings. Many rooftop gardens are arranged on relatively low levels and are overlooked by taller neighbouring buildings. Green surrounding increases the quality of life in the city and is critical in healthy communities. Besides, it is an additional value from the real estate market perspective.

Use of existing underutilised spaces

Integrating food production farms in existing buildings allows us to fully benefit from the potential of a city's dead spaces instead of construct new buildings. It translates directly into financial economies and reasonable resource management.

Run-off delay

Impervious surfaces omnipresent in the cities constitute a huge problem in case of heavy rain. At the same time, because of climate change, extreme weather conditions such as downpours become more frequent than before. Green surfaces have a capacity of absorbing rainwater which reduces the peak flow - the most dangerous moment when all the water flows at once. A part of the water can be used by plants later on and returned to the atmosphere through transpiration and evaporation. Green roof can retain, depending on the region, substrate depth and vegetation type, from 80 % to 100 % of annual precipitations. The vegetation layer of 20 cm to 50 cm can stock from 100 l/m^2 to 250 l/m^2 while thicker than 50 cm even more than 250 l/m^2 (Baumann and Peiger 2018).

Reduction of the heat urban island

The cities are characterised by a huge amount of energy absorbed compared to the energy reflected due to ubiquitous mineral surfaces: roads, walls, roofs. Since the thermal inertia of the city is much more important than in the village, the cities accumulate the heat in the warm season. Moreover, because many obstacles in a densely built-up area prevent air circulation, warm air stays in the city long after the highest heat. The effect of heat urban island is the most visible 1 to 2 hours after the sunset. There is no more effective way to cool the city than using vegetation. Thanks to evapotranspiration, the plants can cool their surroundings while at the same time giving a shade. The reduction of the heat urban island is a very common argument for greening the rooftops. Indeed, it is a great strategy for the cities and many studies confirm the effect of significant temperature reduction by vegetation layers on the roof. However, only when widely applied, it can give the results. Obviously, only open-air vegetation can contribute to air quality improvement and cooling the city. Hence, it refers mainly to soil-based farming and open-air soilless cultures.

Sequestration of CO_2, fine particles, ozone and other atmospheric pollution

Vegetation, due to the process of evapotranspiration, bind the fine particles present in the air. This phenomenon increases air humidity and causes the formation of dew, necessary to fix the dust. It cleans the air and prevents particle movements. Besides, the plants absorb CO and CO_2. As with the argument concerning heat urban island, a massive compensation of the pollution originated from the city must take place to notice the difference. Therefore, introducing food production to the cities constitutes a great tool in urban management to improve air quality but cannot bring considerable changes as an individual initiative. According to the simulation for Bologna, massive food-producing vegetation could capture 624 of CO_2 (Orsini, Gasperi, and Marchetti 2014).

Organic waste reduction

Using organic waste on-site results in reduced volumes of waste managed by a municipality. Also, less green waste is burnt in the incinerator or goes to the landfill. The willingness to reuse precious organic waste was the major motivation to create a garden atop a shopping mall in Sao Paulo, Brazil which now supplies malls restaurant. Thanks to this project, 400 kg of organic waste created every day from the mall's food court, is converted into compost (Novacki 2015).

Overall impact on urban space

All open-air solutions can have a positive impact on urban space providing green surroundings which improves air quality and cools the city. Soil-based farming has additional important advantages — stormwater run-off delay and on site organic waste process to compost. Farming in the greenhouses do not have any positive impact on urban space beside using already existing unused surface.

The experts were asked to evaluate "Impact on urban space" in scale from 1 (very low) to 5 (very high). The median and histogram of their responses compared to my score based on the literature study is in the Table 4.3.

The responses of experts overlap with my assessment.

	my score	expert score	histogram
Hydroponics	3	3	
Aquaponics	3	3	
Aeroponics	4	3	
Soil-based	5	4	

Table 4.3: Impact on urban space of food production methods; author's score based on literature study, median of expert scores from conducted survey and histogram of expert scores.

Chapter 5

Environmental impact

5.1 Energy consumption

Energy demand for lettuce cultivation has been a benchmark for hydroponics and aeroponics. Their energy consumption is significantly higher than of other methods. According to Goldstein et al. (2016) analysing the energy consumption of hydroponics, soil-based rooftop culture and conventional growing of lettuce, hydroponics consumed 22 times more energy per kg of lettuce (152 kWh/kg) than row-farming, represented there by Brooklyn Grange (7 kWh/kg of lettuce), and 2.5 times more than conventional agriculture (60 kWh/kg of lettuce). This study is representative for northern cities with heated greenhouses.

Another research comparing hydroponic energy inputs with conventional agriculture energy use was conducted in 2015 for Arizona. Because of the hot climate, the energy used per kg of lettuce was 6 times smaller than in Boston and added up to 25 kWh. Compared to conventional agriculture the energy use was 8 times higher (Barbosa et al. 2015).

Aeroponics energy use was estimated in the framework of the student project for CombaGroup in Switzerland (Bonzi and Vuadens 2019) and its result added up to 0.445 kWh/kg of lettuce and twice as much as conventional growing.

Depending on the method, energy consumption involves lightning, heating, irrigation, embodied energy.

Lighting

Cultivating plants with hydroponics, aeroponics, and aquaponics all year round requires an appropriate amount of light for the growth. The light is a source of energy for photosynthesis and of signals activating photomorphogenesis and other physiological processes. According to Paz, Fisher, and Gómez (2019), the growth rate, aesthetic quality, and nutritional content are higher with higher daily light integrals. Hence, there is not only financial interest, to maximally take advantage of natural light. Its minimal quantity depends on the plant variety and climate. For CombaGroup, the annual time of lighting for lettuce culture was estimated to 2307 h which demanded 0.394 kWh per kg of salad (min. 16 hours per day)(Bonzi and Vuadens 2019). PlantLab in the Netherlands chose to provide 20 hours of light per day for green leaves which, in turn, adds up to 5800–6300 hours of artificial light per year (Proksch 2017).

In the case of indoor growing systems, the complete reliance on artificial light makes them very energy-intensive. It is assumed that it can be suitable for extreme climates where temperature fluctuations are of bigger concern than the light. Nonetheless, it is possible that no conditions can justify the huge energy needs. Further research is needed to judge it (Graamans et al. 2018).

When it comes to the type of lighting, some sources strongly recommend fluorescent lighting rich in blue light, which causes compact and sturdy seedlings (Brechner M. and Both A.J. 2014). According to more recent studies, the lettuce grown under LED light sources produces more shoot fresh and dry mass than those grown under fluorescent lamps. Either way, growth and quality attributes were claimed comparable under both lamp types (Paz, Fisher, and Gómez 2019). However, LED proponents provide also other arguments: good cost performance, relatively high electricity to light energy conversion factor, varied coloration (spectra), low heat emissions, long lifetime, solid-state construction without gas and significant improvements in the luminous efficiency. Quality of light and its cycle has a significant impact on plant morphology (branching, rooting, flower bud initiation) and secondary metabolite production (pigments, vitamins, etc). Consequently, high-pressure sodium lamps are currently very often being replaced with LED lamps (Kozai 2016).

Heating

Heating growing spaces is relevant in particular in the northern climates that, to prolong the vegetation period, have to prevent too low temperatures. Nonetheless, many sources claim that in such cases, environmental charge due to heating neutralises the benefits from food miles reduction. (Valley and Wittman 2019).

Although it is a minor energy cost, all-year aeroponics requires also the water heating because a specific temperature is needed for roots spraying. The consumption due to water heating was estimated to only about 4 % of total energy use by the system (0.017 kWh) for CombaGroup (Bonzi and Vuadens 2019).

Irrigation and other operational energy consumption

In all soilless technologies, the recirculation pump, air pump, timer, and control systems regulating all parameters constantly consume energy. For CombaGroup (conditioned aeroponics) electricity use due to spraying system which works continually, was estimated to 0.034 kWh, and constituted almost 9 % of overall energy use (Bonzi and Vuadens 2019). Agripolis (open-air aeroponics) uses electricity only for pumps. Soil-production consumes the least electricity — only due to timer (Sanyé-Mengual, Orsini, et al. 2015).

Embodied energy

Controlled environment growing systems are characterised by very high grey energy when compared to conventional agriculture due to greater material extraction and processing for construction. Rooftop greenhouses, which are highly engineered constructions, have even 75 % greater impact than basic soil-based tunnels because of a large amount of polycarbonate used for construction (Pons et al. 2015). Another material with very high embodied energy is steel used for structures.

The second aspect, which has a significant grey energy charge, is equipment. For example, glass fiber-reinforced polyester used for 100 m^3 water tank at ICTA-ICP Lab (see subsection 4.2.6) rooftop greenhouse constitutes from 10 % to 25 % of environmental impact at manufacturing stage (Proksch, Ianchenko, and Kotzen 2019). While calculating embodied energy, it is always important to consider the lifespan of the material. For instance, PVC used for piping in aquaponics has high grey energy but can last up to 75 years. In some cases, it might not be necessary to invest in such longevity and it is better to reduce environmental impact by more ecological choices. The footprint of the vegetated rooftops is not very high. It is defined by the substrate, type of vegetation, and origin of biotope structures.

Overall energy consumption

Given the high energy inputs necessary for running of the conditioned systems, the plausible scenario is when renewable energy can meet all onsite demands of the building. Al-Chalabi (2015) aimed at quantifying of energy flows in hydroponic vertical farm according to the concept of Dr. Dickson Despommier, a father of vertical farm concept. His design was chosen as a model because it was claimed to be the most realistic, practical and appropriate from all existing options. It is very interesting to see the results for somehow the "ideal" model. According to the authors, there are two crucial factors for the energetic efficiency of the project. The most important was to find optimal dimensions of the building to balance energy demand and generation on site. The more area the building occupies, the more energy for it consumes but also produces. Its final dimensions should be the result of energy optimisation — not of an architectural concept. Secondly, the aspect able to reduce energy demands is maximal exposure to sunlight.

In northern cities there is need to lighten the plants longer and heat greenhouses to prevent temperature stresses. Soilless technologies are a much more viable solution in mild climates due to the lack of heating requirements and longer periods of sunlight exposure. Energy inputs necessary for farming in cold climates can overwhelm the benefits of reduced food miles making urban agriculture in the north a non-viable solution. At the same time, the urge to find self-reliance concerns much more northern cities.

The experts were asked to evaluate "Energy consumption" of each method in scale from 1 (very low) to 5 (very high). The median and histogram of their responses compared to my score based on the literature study is in Table 5.1.

Soil-based farming demands energy only for a timer and sometimes for irrigation, while conventional agriculture needs energy for fertilising and seasonal machine work. Their consumption is comparable and assessed as medium, both by me and by experts. Given climatic variabilities, as well as different variants in complexity and equipment of each soilless method, it difficult to compare energy consumption. In principle, the more northern the location is, the more energy on heating and lightning it demands. When compared to the soil-based method, soilless technologies are very energy-consuming, even in favourable conditions. That is why I evaluated their energy consumption as very high. Surprisingly, the experts did not find those methods so energy-intensive.

	my score	expert score	histogram
Hydroponics	5	2	
Aquaponics	5	3	
Aeroponics	5	2	
Soil-based	3	3	
Conventional	3	3	

Table 5.1: Energy use for food production methods; author's score of productivity based on literature study, median of expert scores from conducted survey and histogram of expert scores.

Undoubtedly, there is a significant gap in the research in terms of energy use. The existing literature provides very fragmentary data. Ideally, different methods with comparable expected yields should be compared in the same localisation. Secondly, a study comparing the same methods under different climatic conditions would allow us to see how energy consumption changes with latitudes. Finally, the limits of acceptable energy use per kg of yield should be determined so as not to exceed the reasonable input.

5.2 Water consumption

All soilless technologies (hydroponics, aquaponics, and aeroponics) outstand the conventional culture in terms of water usage. The only water loss is due to the evapotranspiration of plants and the periodic flushing of the nutrient solution. The systems function as closed loops, which means that there is no wastewater.

It may seem counter-intuitive, but even in hydroponics, there is no water replacement. Keeping the same water provokes the development of microorganisms that are necessary for plants to grow. Over some time, the water has already a good supply of beneficial bacteria that prevent harmful fungi and algae from growing, and also help support the growth of the plants to full maturity. However, to have control over the quality of water, the system of pumps works continuously to deliver a steady stream of nutrient solution to the plants' roots. The smallest amount of water is used in aeroponics, although the sprayers moist the plants continuously. It is because the droplets are generally in the size range of 30 microns to 80 microns creating a kind of a fog environment. Rooftop soil farms are closer to conventional agriculture in the amount of water used. According to a Life Cycle Assessment, 75 % of the overall impact of soil-based production is due to water consumption (Sanyé-Mengual, Orsini, et al. 2015). Therefore, there is a strong interest to optimise the water use.

For row-farming, irrigation is necessary, particularly when the larger rooftop is at stake. Very efficient, low cost and popular technique is drip irrigation. Drip lines can be covered by 5 cm of the soil or pass on the surface. Also, low aerial sprinklers are used very often. To prevent unnecessary use of irrigation and react only when there is a need, rainwater sensors and moisture sensors are used. Besides, mulching becomes a top priority technique to keep the soil humidity and economise water. In permaculture, mulching is considered the basic practice guaranteeing healthy soil and better yield - thus, enhancing the functioning of the whole system. Hence, on rooftops, even those who are not aware of it, become somehow permaculture practitioners.

The experts were asked to evaluate "Water consumption" of each method in scale from 1 (very low) to 5 (very high). The median and histogram of their responses compared to my score based on the literature study is in Table 5.2.

The differences between my grades and experts' scores are quite considerable. Firstly, soilless technologies outstanding in terms of efficient water use got all grade 1, indicating very low water consumption. Surprisingly, aeroponics was assessed as highly water-consuming (while being the most effective), and aquaponics and hydroponics, medium water-demanding. Secondly, experts found soil-based technology comparable in terms of water use with alternative methods, while its water consumption is significantly greater and similar to industrial agriculture. Conventional agriculture, which has an uncontrolled and inefficient water system and does not rely on rainwater harvesting, got the highest grade from me.

	my score	expert score	histogram
Hydroponics	1	3	
Aquaponics	1	3	
Aeroponics	1	4	
Soil-based	4	3	
Conventional	5	2	

Table 5.2: Water consumption for food production methods; author's score of productivity based on literature study, median of expert scores from conducted survey and histogram of expert scores

5.3 CO_2 emissions due to transport

The argument of short circuit is one of the most frequently evoked in favour of urban farming (Despommier 2013; Sanyé-Mengual, Martinez-

Blanco, et al. 2018; Benke and Tomkins 2017). It is estimated that an average meal is transported about 2400 km before it appears on our plate (Gentry 2019). Although this is not without its impact on the environment, the aspect of CO_2 emissions due to the transportation process seems to be oversimplified.

Firstly, we have to take into account that CO_2 emissions vary depending on the means of transport. A study made in the UK in 2004 analysed the levels of CO_2 emissions by each category of transport: road, rail, water and aerial. In the evaluation of ecological footprint, the crucial thing is the relation between CO_2 emissions and the weight of product transported capacity expressed in CO_2 per tonne-km. Road transportation has more than 15 times greater environmental impact than rail transportation which produces 13.9 g CO_2/t km. In road transportation itself, there are also huge differences. For example, vans have much more significant CO_2 impact than lorries producing 14.5 % of the total CO_2 emissions from the road freight sector to carry only 6.6 % of road tonne-kms (Mckinnon 2007).

Secondly, a key factor in the evaluation of CO_2 emissions is the importance of the last mile. It is in the majority of cases the distance done by customers which makes it extremely difficult to estimate because of relative distances as well as different choices of clients. Using a bicycle or shopping on foot can significantly reduce the footprint, whereas transporting small amounts of merchandise on relatively short distances (shop — home) by car has a very high CO_2 footprint in a whole transportation chain. Food miles are, thus, only a part of the picture.

Environmental savings associated with the avoided distribution stage, have to be quantified individually for each case taking into account an alternative vegetable source. For one city it can be 900 km, for another 50 km.

In this regard, the chain supply of urban farming has to be very well considered to use an argument of reduced carbon footprint when compared to conventional agriculture. Many existing farms cooperate with the facilities located in the same building as a food production unit. Supplying nearby restaurants, school canteen, the hotel has the advantage of zero or minimum transport when compared to sales to private clients. CO_2 emissions due to transport are independent of the technology used by a food production plant. All of them have the potential of being zero transport while well-integrated in the local market.

The experts were asked to evaluate “CO_2 emissions” of each method in scale from 1 (very low) to 5 (very high). The median and histogram of their responses compared to my score based on the literature study is in Table 5.3.

The experts claimed the CO_2 emissions higher than me. However, this category is very case dependent and difficult to generalise. I concentrated on the potential of urban farming to emit low quantities of CO_2 due to transport but in reality, many examples are not optimal.

	my score	expert score	histogram
Hydroponics	2	4	
Aquaponics	2	3	
Aeroponics	2	3	
Soil-based	2	4	
Conventional	4	3	

Table 5.3: CO_2 emissions of food production methods; author’s score of productivity based on literature study, median of expert scores from conducted survey and histogram of expert scores.

5.4 Biodiversity

A surface of the rooftop can provide habitat compensation for species affected by land-use changes.

Urban farms have a strong interest in attracting particularly pollinators. There are many recent examples of apiary installation on the rooftops. Among the most interesting ones, we can mention a rooftop of Upper House in Sweden on the 27th store, Eurocenter Office Complex in the centre of Warsaw, or almost 700 of beehives in Paris.

It is important to remember that honeybees are responsible for only 15 % of pollination. Hence, it is necessary to provide a nest also for other pollinators such as bumblebees, wild bees, butterflies, hoverflies, and even bats. A great strategy for larger soil-based farms is also integrating chickens on the rooftop farm which is a smart pest management practice.

The group of animals that greatly benefits from green rooftops is birds. Recently, a radical decrease in bird population has been observed because, among other things, of the lack of space dedicated to fauna in the cities. Green rooftops offer a great possibility to nest for sparrows, blackbirds, goldfinches, black redstarts.

To support specific species such as spiders, wild bees or beetles, it is important to provide diverse natural elements on the rooftops, such as logs, stones, wood, sand, gravel of different granulometry. Such wild corners, always recommended in permaculture design, result in well working, auto regulating system, and hence, better yields.

However, some species cannot reach or survive on the roof. Earthworms, for example, such precious allies in soil cultivation are unable to withstand extreme temperatures on the roof (Brenneisen 2003). Because of the limited depth of the substrate, they can not escape to cooler layers of the soil in the summer.

The sustainability of the system can be reached when there are multiple interactions between species and their force is variable. The greater the number of species, the less important each reaction is and the more resilient the system is. Interestingly, the biological diversity of plants and animals is sometimes even stronger in urban zones than in the rural countryside. It is due to a great variety of spaces in contrast to the monotonous rural countryside. Green infrastructure like roofs, living walls or rain gardens contribute to the biodiversity in the urban zone and allow to provide a continuity of green areas that serves a passage as well as a shelter during migrations. Connectivity is a very important concept in urban biodiversity planning. In Switzerland almost every village and canton have the tools to support urban planning with regard to biological corridors [1]. Basel made green roofs

[1] `www.lausanne.ch/vie-pratique/nature/la-nature-et-vous/bonnes-pratiques-conseils-nature/reseau-ecologique/organisation-fonctionnement.html`

its key strategy of boosting biodiversity in the city. Consequently, roof vegetating is there a mandatory practice for all new flat roofs.

Regardless of technology, all open-air farms can contribute to biodiversity enhancement. However, since soilless methods are more frequently used in greenhouses, their positive impact is limited.

The experts were asked to evaluate "Biodiversity enhancement" of each method in scale from 1 (very low) to 5 (very high). The median and histogram of their responses compared to my score based on the literature study is in Table 5.4. Our evaluation of all methods coincides.

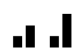
	my score	expert score	histogram
Hydroponics	2	2	
Aquaponics	2	2	
Aeroponics	2	2	
Soil-based	4	4	
Conventional	2	4	

Table 5.4: Biodiversity enhancement for food production methods; author's score of productivity based on literature study, median of expert scores from conducted survey and histogram of expert scores.

5.5 Possible cultures

The best plants to be grown under hydroponics and aeroponics are different types of green leaves and aromatic herbs — they grow quickly and densely, and bring profits. An important obstacle for hydroponics is that only 2–3 varieties of plants can be grown using one pump and one nutrient tank because every plant has different nutrient requirements. To be able to grow more varieties, more equipment is necessary and more expensive it is to install and run the system. Even

		BASIL	BEETS	CARROTS	CELERY	CUCUMBER	EGGPLANT	KALE	LEEKS	LETTUCE	MINT	ONION	PARSLEY	PEPPER	RADISH	ROCKET	SPINACH	TOMATOES	ZUCCHINI
SOIL-BASED	**CONTAINER** 11-19 L	●				●	●	●	●	●	●	●	●	●	●	●	●	●	●
	RAISED BEDS																		
	10 CM									●			●		●	●	●		
	30 CM	●				●	●	●	●	◼	●		◼	●	●	◼	◼	●	●
	45 CM	◼	●	●	●	●	●	●	◼	◼	◼	●	◼	●	◼	◼	◼	●	●
	ROW-FARMING																		
	30 CM	●				●	●	●	●	●	●		●	●	●	●	●	●	●
	45 CM	◼	●	●	●	●	●	●	◼	◼	◼	●	◼	●	◼	◼	◼	●	●
HYDROPONICS	GREENHOUSE	●				●	●	●		●	●			●		●	●	●	●
	OPEN-AIR	●					●	●	●	●		●	●	●	●	●	●	●	
AEROPONICS	HORIZONTAL	●				●	●	●	●	●	●	●	●	●	●	●	●	●	●
	VERTICAL	●						●		●	●		●				●	●	●

◼ STILL POSSIBLE BUT ALREADY UNPROFITABLE

Figure 5.1: Plants possible to grow with different methods

if it is technically possible to cultivate quite an impressive range of vegetables and fruit, only the most economically viable ones are chosen. The plants that need to have a root in the soil like potatoes, radish, carrots, or beetroots can not be grown without soil.

An important advantage of the aquaponic system is the fact that it includes fish breeding. Plants growing in aquaponics is a secondary system. The most popular fish species in aquaponics is undoubtedly tilapia which is highly tolerant of fluctuating water parameters. Other common species are rainbow trout, channel catfish, jade perch, and goldfish (Goddek, Joyce, Kotzen, et al. 2019).

Soil-based culture gives a lot of possibilities in terms of plant varieties. Only 10 cm is enough to grow salads and herbs. From 15 cm, it is already possible to grow most Brassicas (e.g. broccoli, cauliflower, kale, and collards). 45 cm is an optimal depth to cultivate Solanums (e.g. tomato, eggplant) and the majority of root vegetables such as beets or carrots. To maintain soil health, crop rotation, cover cropping, succession planting diversification, and relay planting are all the key factors that determine plant diversity.

	my score	expert score	histogram
Hydroponics	2	2	
Aquaponics	2	2	
Aeroponics	2	2	
Soil-based	4	4	
Conventional	5	4	

Table 5.5: Amount of possible cultures for food production methods; author's score of productivity based on literature study, median of expert scores from conducted survey and histogram of expert scores.

The types of plants possible to grow with different methods are presented in Figure 5.1. The experts were asked to evaluate "Possible cultures" of each method in scale from 1 (very low) to 5 (very high). The median and histogram of their responses compared to my score based on the literature study is in Table 5.5. Our grades were the same except for conventional agriculture.

5.6 Fertilisers and chemicals

The use of fertilisers, herbicides, and pesticides is a common practice in conventional agriculture to maximise the yields. The pesticides and herbicides are the chemicals or biological agents whose function is to protect plants from pests, fungi, diseases, and weeds. The pesticide era is said to have started about 1940 when the first synthetic agents were manufactured. Nowadays, 70 % of all pesticides are used in developed countries. Due to their widespread and uncontrolled application, it is difficult to find a place in the world untouched by their presence. Their traces are regularly found in soil samples, tree bark in the forests, the polar bear grease, and even umbilical cord of newborns (Dodds W.K. 2008). The impact on foetus is the most alarming. We already know that some pesticides act like hormones. They are called endocrine disruptors because they send false signals in human bodies. The earlier and earlier time of going into puberty of young girls as well as breast cancer morbidity is claimed to be the result of pesticide exposure[2].

As for fertilisers, they have been used for ages. Their main function is to enrich the plants in nitrogen, phosphorus, and potassium that enable their growth. The main problem with fertilisers is their overuse. The injection of vast quantities of nitrogen and phosphorus into the environment through chemical fertilisers caused a huge rupture in a natural nitrogen and phosphorus cycle. That, in turn, destroyed the soil capacity to develop the closed-loop supporting perpetual soil fertility working for thousands of years and resulted in soil depletion.

The second problem with fertilisers is that they are synthetic. In commercial agriculture using organic fertilisers is not economic because it is more expensive, demands more labour to apply, the nutri-

[2] Andre Leuwww.farmingsecrets.com/what-sort-of-society-poisons-its-children/

ents are released slowly and their ratios can not be guaranteed. Synthetic fertilisers outperform organic ones in all those aspects but have huge consequences: the buildup of toxic substances in the soil, its uncontrolled leakages and depletion of nutrients in the soil. The final consequence is the long-term degradation of essential natural systems and aquatic ecosystems. Besides, the distribution of fertilisers is done by machine and constitutes 40 % of energy use in conventional agriculture. Soil-based rooftop gardens and farms have a particular interest in building healthy soil which, in the majority of cases, is using only compost, mulch, and organic fertilisers (see the example of Brooklyn Grange). The exception is a culture in containers that cannot build the soil and demands fertilisation.

In aquaponics, any use of pesticides and herbicides is excluded because it could have a negative impact on fish (Grozea and Blidariu 2011). The nutrients necessary to plant growth come from a fish uneaten feed and feces. Aquaponics is apart from all other technologies by its extremely efficient nutrient utilisation. To compare, the standard RAS system wastes about 75 % of nutrients added to the system. It is because the fish use only 25 % to 35 % of nutrient included in the feed. Aquaponics benefits from all the nutrients to cultivate plants (Lennard 2017). In the basic type of aquaponics — a coupled system — water circulates in one closed loop between fish and plants (Figure 2.2A). However, one of the major challenges in cultivating plants in such a way is that the nutrient solution produced by fish does not necessarily contain optimal nutrients for plant growth. Such a system demands a very careful combination of fish and plants and some compromises in terms of water pH, temperature, and nutrient concentrations (Goddek, Delaide, et al. 2015). To obtain a higher yield, it is advantageous to partially fertilise certain lacking nutrients such as phosphorus, potassium or magnesium. The amount of fertiliser acceptable for fish in the system is 50 % of the regular dose in pots with soil. In the multi-loop aquaponic system, it is possible to use even more additional substances to boost plant growth and optimise the conditions for both fish and plants.

In hydroponics and aeroponics, the quantity of nutrients supplied to plants is precisely contained to cover the needs of plants to grow. For 1 kg of lettuce, the amount of nitrogen, phosphorus, and potassium needed is respectively 6075 mg, 675 mg, 6750 mg. For each culture, the formula of fertiliser is composed differently. Since the decrease by 15 % in the lettuce growth was observed, when the nutrients were overdosed and accumulated in the water, there is no interest to exceed the dose assigned to each variety. In soilless technologies, synthetic fertilisers are preferred over the organic ones. The nutrient content of liquid fertiliser deriving from compost or manure is never precise, and there is a risk of contamination. Another trouble is that organic nutrients are difficult to dissolve and tend to clump up within the system, which can result in clogging the pump and losing all the plants [3]. Soilless cultures have an advantage over conventional in-ground production as they conserve freshwater reservoirs (no use of pesticides, herbicides and nor wastewater). Although the vegetables grown in hydroponics and aeroponics are very often called organic, they cannot officially obtain such labels. Organic is reserved for soil-grown products.

	my score	expert score	histogram
Hydroponics	3	4	
Aquaponics	2	4	
Aeroponics	3	4	
Soil-based	2	3	
Conventional	5	3	

Table 5.6: Fertiliser use for food production methods; author's score of productivity based on literature study, median of expert scores from conducted survey and histogram of expert scores.

The experts were asked to evaluate "Use of fertilisers and chemi-

[3]https://originhydroponics.com/best-fertilizer-nutrients-for-hydroponics/

cals" of each method in scale from 1 (very low) to 5 (very high). The median and histogram of their responses compared to my score based on the literature study is in Table 5.6. In my evaluation, I wanted to highlight the difference between intensive chemicals use practices of industrial agriculture and smaller amounts of precisely dosed fertilisers for soilless methods. It is important to distinguish from soilless methods, the aquaponics with its potential to work even without additional fertilisers. I assigned low fertiliser use also to the soil-based method because many examples prove that such farming is entirely organic.

Chapter 6

What form of agritecture?

6.1 Impact analysis by group of criteria

To assess the overall impact of each method on three groups of criteria (social, spatial and environmental), I grouped all the experts' answers in the relevant category. Each group contained a different number of evaluation criteria, therefore I gathered them into normalised histograms (Figure 6.1). High values in the histograms correspond to positive and low values to negative evaluations. There were some criteria (for instance energy consumption), where originally high grades were not positive. In such cases, for the sake of comparison, I reversed the scale and, for example, 4 (high consumption) was translated into 2 (low grade). Having analysed the criterion of human resources, I considered it neither explicitly positive nor negative, regardless of the grade assigned. Therefore, I decided not to include it in the final histograms.

Experts' evaluation of social method were the highest for aquaponics and soil-based method but there were no significant disparities among other methods. Lower grades of soilless-methods for impact on communities were balanced by their high productivity.

In the spacial group of criteria, the most positive assessment gained soil-based method. From soilless methods, aeroponics performed the best due to the easiest adaptation to existing structure but also unfounded high grade in synergies. Hydroponics got the lowest notes but no method received score 1.

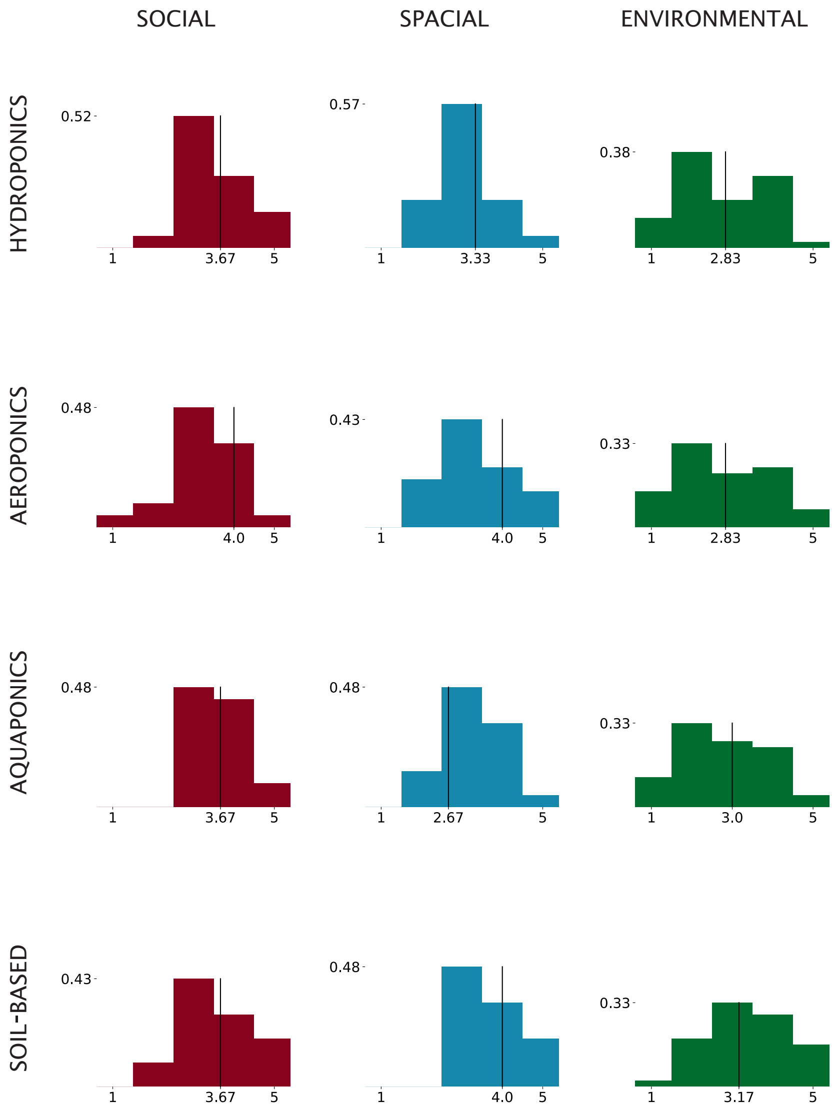


Figure 6.1: Histograms presenting answer spread of experts for each method and 3 groups of criteria; vertical line indicates the average evaluation of my scores for each group of criteria.

As for the environmental group of criteria, soilless methods received a lot of low notes and the soil-based method performed the best from all. Although the environmental aspect was the most quantitative of all, the spread of grades was quite large. Energy use, water use, possible cultures, CO_2 emissions are all the criteria that operate with numbers, hence, they should be easy to assess. However, there are significant disparities in data provided by literature which is probably the reason for those differences in experts' evaluation.

6.2 Sustainability

Architecture has notably the interest to develop and promote sustainable solutions — according to definition, causing little or no damage to the environment and hence, being able to continue for a long time. First, we should define what factors influence this quality to endure with no harmful effects to environment.

The sustainability of soilless methods which demand a lot of resources, notably energy input, is at first place conditioned by the availability of renewable energy. Soilless methods are the most viable where land is expensive, water is scarce, and the soil is poor. Simplified hydroponics is often seen as a sustainable long-term solution for low-income families but as we could see on the example of Gaza Strip, lack of expertise and funds have caused the project to collapse. The systems did not sustain despite fulfilling initial criteria. Hence, another important factor affecting sustainability is the access to necessary inputs of a particular system (nutrient solution or feed for fish) and to expert support.

The ability to sustain of soilless methods is entirely depending on specific maintenance and regular control. As opposed to the natural environment which has a certain resistance to external factors and ability to survive and regenerate each year without human intervention (perennials), the high-tech production methods are extremely fragile systems depending entirely on humans. As a result, in case of any problem (power cuts, malpractice, etc.), the whole production is lost.

Soil Association chief executive Patrick Holden commented on the subject very aptly: "Feeding plants through chemical nutrients in solution is analogous to feeding a human patient in hospital by intravenous solution. That is valuable in treating serious ill-health in humans, but in relation to food production, it excludes the vital role of soil as "the stomach" of the plant in breaking down organic matter and completing nutrient cycles, on which many planetary ecosystems ultimately depend."[1].

This means that soilless methods should be the last resort where other food production is not an option. For example in aquaponics, high resource consumption may be outweighed by potential environmental damages caused by overfishing. Since per capita fish consumption continues to rise at an annual average rate of 3.2 % (double the rate of population growth) (Goddek, Joyce, Kotzen, et al. 2019), aquaponics is probably, despite its flaws, the technology of the future. As far as fruit and vegetables production is concerned, efforts to repair the local food system should be directed elsewhere. Servigne (2013) suggests that the most effective way supplying the market with fresh produce would be the network of microfarms such as famous permaculture farm Bec Hellouin in Normandie, France. Such farms are not only highly productive but also able to regenerate the soil and ecosystems.

Sustainability of soil-based method integrated into buildings is conditioned mainly by water management system but also farming practices. It is important that plants were diverse and the fertility of the soil maintained. Rainwater should be harvested regardless of the climatic conditions to guarantee the stock in case of extreme weather conditions. Soil-based technology which combines the advantages of green roofs and urban gardening brings benefits in both urban and social dimension. Hydroponics and aeroponics should not be seen by definition as universal sustainable solutions of the future. The relevance of their application should always be evaluated for a specific location with privileging of soil-based alternatives.

[1] www.sustainablefoodtrust.org/articles/vertical-farming-and-hydroponics-on-the-spectrum-of-sustainability/

6.3 Practical guidelines

Among three options for building integration (wall, interior and the roof), we have the greatest interest to introduce food production on the latter because it gives the widest range of possibilities and does not compete with uses of a building's interior. While designing new buildings, it is recommended to facilitate potential use of the roof in the future, even if the project initially does not include such a function. Urban space changes very dynamically and should be ready to respond to changing need of their users.

There is a great principle in permaculture design saying that every element should fulfil more than one function, ideally at least three. Such an approach in architecture results in reasoned design optimal in terms of input and output. Contrary to vertical farms which are strictly commercial and fulfil only one function of food production, building-integrated urban farms are in most of cases multifunctional. They introduce diversity to the built environment and create more resilient cities.

For more positive social and environmental impact, we should rather privilege low-tech solutions with the soil-based method at the forefront. We should remember that all soilless methods exist in simplified, even do-it-yourself versions, which can be suitable for personal, small scale use. There also might be some cases where more high-technology solutions are justifiable — in water-scarce regions, in case of no arable lands (soil regeneration is possible even on the desert but it takes time), and sites with the access to a renewable energy source. Our starting point when choosing the method should always be the climate and available resources. A simplified decision tree (Figure 6.2) can be used as a tool helping to choose an appropriate solution for a given site.

At the same time, architecture should first of all focus on creating green, versatile *spaces* which among many functions makes gardening possible, than on food production itself. The issue of the most effective integration and proper design should be better investigated and propagated among architects and planners. It would be desirable if the communication between architects and specialists of food production systems was more propagated. Although architects do not

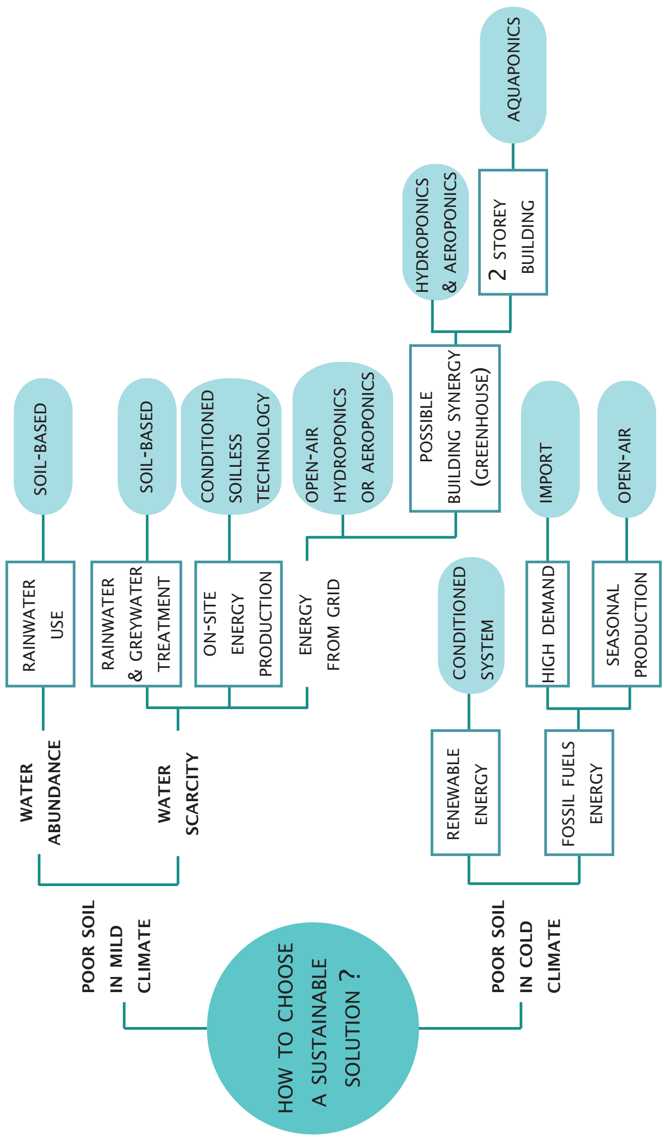


Figure 6.2: Decision tree for quick assessment what kind of building integrated food production is suitable for given conditions.

have to know everything, they need to be up to date and cooperate at the interdisciplinary level. Finally, certain knowledge is necessary to shape a sort of criticism towards trends and other promoted for some reasons solutions. Searching for answers to the questions what kind of architectural forms of food production do we have the interest to develop, allowed me to understand to some extent, how to distinguish between sustainable solutions and other green-labelled ones.

6.4 Final remarks

The objective of this study was to bring the topic of building-integrated food production closer to architects and facilitate their design choices with the consciousness of their impact. This study is a broad review of scientific literature presenting all key aspects viewed from the architect's perspective. It explores the relevance of different arguments in this very topical debate about building-integrated agriculture and provides clues for the application of different methods in a given context. To present not only the literature review but also experts' point of view, I chose to use scores for each aspect. However, translating the complex issues on one grade, was in many cases difficult both for me and for experts. In my opinion, it constitutes the main limitation of my work.

Still many issues require more research in the domain of building-integrated agriculture. Firstly, the contentious topic of food quality comparison for each method needs a systematic study. Both nutrient content and undesirable residues of chemicals in control samples of industrial agriculture products should be taken into account. In some cases, it might be about choosing the lesser of two evils — fewer nutrients versus more nutritious but contaminated food. In the soil-based method, it is crucial to well describe the origin and the content of samples because they can vary diametrically.

Secondly, the relevance of conditioned systems in cold climate remains unclear. For the time being, the first studies assume that the footprint of conditioned systems can outweigh the footprint of imported food. However, it needs to be scientifically justified. The examples of vertical farms in the north have already started to multiply, promoted as a sustainable solution of the future. From a scientific point of view, it might be considered as a chance, because real cases can be analysed. This subject remains urgent to investigate.

Thirdly, the Life Cycle Assessment method needs to be used to assess the ecological impact of different solutions in various latitudes and climates. Research should focus on the comparison of the methods under different climatic conditions. Special attention should be paid to energy use in soilless methods depending on climate since there is a lack of literature in this vital subject. A systematic study showing the necessary energy input changes is needed.

Finally, a very up-to-date issue of building synergies, especially interesting for architects should be more investigated. Although, the concept is present in the literature, there are still very few examples of synergies. The energy and water economies should be evaluated in relation to the resources needed for the integration of food production unit.

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