The Elegance of VERTICAL FARMING

ARCHITECTURAL DESIGN OF BUILDING INTEGRATED PFAL

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The architectural integration of Plant Factories with Artificial Lighting (PFAL) into the urban environment, optimising social and aesthetic potentials without compromising production quality and efficiency.

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The Elegance of Vertical Farming

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PREFACE

Personal Fascination
My interest in the area of *vertical farming* is derived from my fascination for: architecture & aesthetics, entrepreneurship & innovation and a family background in floriculture. Initially I applied for Explore Lab with a different topic, but found it could not quite fulfil my ambitions for my (likely to be) last year as a TU Delft student. I strive to design a structure that inspires users of the space and expands their perception. Something the structure I was initially planning on could certainly achieve (an architectural translation of a *Strand Beest* by Theo Jansen), but I struggled with the business case or in other words, the potential to be realised. Which clashes with my fascination of entrepreneurship, resulting in a thought of doubt during the summer holidays prior to the start of my graduation project.
Halfway through this summer period I attended an Applied Physics MSc graduation presentation from a friend of mine, who had researched glass coatings for greenhouse growing which increase photosynthesis (at PHYSEE a YES-Delft start-up). In an enlightened few days I had found the graduation topic that incorporated the exact fascinations that I strived to explore during this year. I discovered vertical farming to be an emerging multidisciplinary field, which I believed would benefit from input of an architectural perspective early on in the development to help reach its full potential.

Naturally, I want to express my gratitude towards Andy Jenkins & Elise van Dooren for all the insightful discussions and knowledge you have given me during the Research Phase of this project. In times of COVID-19, it is not easy to connect with likeminded individuals and therefore I am grateful to those that were still willing to connect with me even if it was merely through the digital world of Zoom. Although this thesis focusses on the Research Phase, I want to extend my gratitude to Ferry Adema who together with Elise has guided me through the design phase. Lastly, thank you to all my friends and family who supported me along the way.

Graduation Project
This project consists of two intertwined phases; Research and Design.
The Research Phase addresses which factors are relevant for architects when designing building integrated Plant Factories, looking to identify where the room for a creative interpretation lies while maintaining production quality and efficiency.
The Design Phase explores this design freedom in the context of De Randstad (The Netherlands), by designing two structures that integrate multiple entities of the supply chain of agriculture, into the urban environment;

- Community scale PFAL integrated with a supermarket and residences.
- PFAL Experience Centre integrated with a distribution centre.

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ABSTRACT

With phenomena such as population growth and urbanisation, expanding cities no longer derive their food supply from their hinterlands but rely on the global food trade which includes vast open-field agriculture. Given the limited availability of land, water and nutrients together with the uncertainty of a changing climate, the sustainability of these networks becomes questionable.
Urban agriculture and in particular Plant Factories with Artificial Lighting (PFAL) offer the potential to positively adapt to these changes. In these PFALs, horizontal trays are stacked in a closed environment, using LEDs, HVAC and hydroponic systems to enable an optimal environment for plant growth. Besides the bottleneck of high energy demands, an architectural problem is emerging: when approached from the perspective of production quality and efficiency, PFALs are at risk of being architecturally translated as a closed box. Resulting in production nearer the consumer, yet these consumers remain oblivious about the making of what they consume on a daily basis.
This project aims to enable the architectural design of building integrated PFALs in such a manner, that the consumer and other involved actors benefit not only from the product but also learn about and experience the growth process, while retaining production quality and efficiency. To achieve this, a factor list is derived from existing literature, to provide a document for architectural reference when designing building integrated PFAL.

Key words
Vertical Farming, Urban Agriculture, Agritecture, PFAL, Architecture, Urban environment, The Netherlands, Building Engineering, Biophilia.

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INTRODUCTION

1. A Historic Overview of Agriculture

How Food Shapes Our Lives

Until half a million years ago our ancestors, at the time consisting of the species *homo neanderthalensis*, *homo heidelbergensis* and *homo erectus*, were nomadic hunter-gatherers who spent their lives tracking the annual migrations of the beasts that formed the basis of their diet. Though having discovered the ability to spark a fire, life was essentially peripatetic.

After the last glacial period made way for highly fertile grounds around 12.000 years ago, diets other than meat started to develop and with it came the harvesting of wild grain. These pioneers of farming were no longer required to follow the annual migrations and thus started settling down.

Moving ahead in time to the *polis* of Athens, one of the forces driving people to live in these predecessors of modern cities was the collecting and distributing of food. In the Greek *polis* and Roman *civitas,* the rural hinterland was just as important as the inner parts of the city. As prosperity grew, so did the population of cities. Requiring more food to sustain itself, these hinterlands gradually started expanding until the distance of transport became too expansive to compete with the nearby city lands. For a while, this kept city sizes in check, until in the 1800s when railways were invented. Opening up a wide range of possibilities, including that of transporting food over great distances of land, enabling the growth of urban populations (Steel, 2013).

By the end of the 19th century, unhygienic market squares where citizens had to endure the smell of faeces all day were gradually done away with. When privately owned cars became a commodity, food started shifting from local markets to large-scale supermarkets and shopping malls outside the city. Thus so it transitioned from less unhygienic markets to no markets at all. However, in recent years a less smelly variation of these traditional markets is starting to re-emerge in Western societies, to fill the demand for a more culinary experience.

Occurring phenomena & resulting challenges

The world population is predicted to grow from 7.8 billion in 2020 to 9.8 billion by 2050 (U.N., 2018). Currently, over half of these people live in cities and an additional 2.5 billion people are expected to join them of which 90% across Asia and Africa (U.N., 2018). To feed the world's population, approximately 50% of the habitable land on our planet is required for agricultural purposes (Ritchie & Roser, 2019) *(fig. 1).*

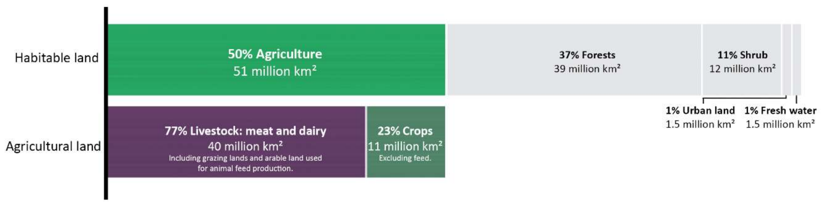


Fig. 1. Global land use for food production. Adapted from Searchinger et al. (2019).

To produce enough food for the predicted increase of 2 billion people while continuing current means of food production, cropland and pastureland are projected to increase by nearly 600 million hectares (Searchinger et al., 2019). The most (economically) plausible way to do so is through economies of scale, reducing production costs per product by spreading out the fixed cost over a larger output number. These massive plots of farmland are cheapest when far away from residential real estate. In other words, far away from the consumer. Besides a reduction in nutritional quality of the food because the focus lies on providing a long shelf life, transportation costs become a key component in the products economic viability. This cost is currently only expressed through monetary value, while the environmental cost (damage dealt to the environment through emissions) is not taken into the equation.

Partially as a result of a changing climate, extreme weather conditions such as long periods of draught, (hail)storms and floods become increasingly common. These occurrences damage crops and can even cause complete harvest failure, putting great pressure on food supplies.

Besides the unsustainable factor of transportation, a major percentage of food production itself is not exactly sustainable either. The agricultural sector accounts for 70% of global freshwater consumptions, 22-25% of global greenhouse gasses and used over 11% of habitable land for horticulture crop production and 39% for livestock (Odegard et al., 2015; Ritchie & Roser, 2019). In addition, if more land becomes depleted and forests are burnt to acquire the needed farmland, natural ecosystems responsible for biodiversity and climate change mitigation will crumble (Searchinger et al., 2019). An example of desertification caused by deforestation and depleted farmlands is the Gobi desert which is closing in on Beijing (Batjargal, 1997). Searching et al. (2019) point out the following:

> Agriculture has not been a major focus of emissions mitigation, other than as a potential source of carbon sequestration in soils. Yet farming is a significant and growing source of emissions. To limit agriculture to its "fair share" of total allowable emissions in a world where global temperatures have risen by 2 degrees Celsius, the sector must address the demand for 50 percent more food while reducing emissions by two-thirds from 2010 levels. And to stay under a 1.5-degrees Celsius rise in temperature, these emissions will need to be further reduced by reforesting at least 585 million hectares of agricultural land freed up by productivity gains and reductions in demand (p.iv).

With cities deriving their food supply from increasingly distant sources across the globe, not only the physical separation between food and its consumer is increasing, also the knowledge discrepancy of consumers about their food is expanding. Thus, the individual is losing their grip on eating food that suits their nutritional and cultural needs. An overview of these phenomena and challenges is given *(fig. 2)*, with the critical note that these are merely the most prominent aspects and some challenges can partially result out of other challenges.

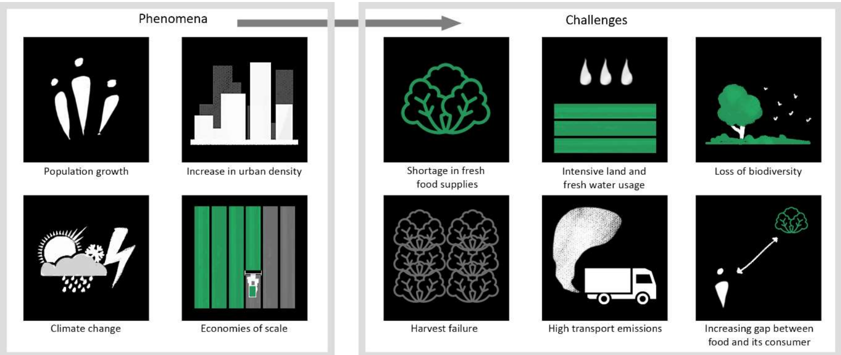


Fig. 2. Overview of most prominent phenomena and challenges leading to urban agriculture as potential solution.

Netherlands

Translating these phenomena to The Netherlands (Derkzen & Wiskerke, 2008; Lestari, 2017; Nabielek et al., 2016); more than 75% of the population already resides in urban areas, a number which is expected to increase especially for the Randstad. With this, an ancestral rural way of living and working is left behind. Agriculture-wise, the ambition or necessity of meeting sustainability goals lays an increasing pressure on farmers, challenging their conventional practice. Counteracting this shift from rural to urban is a growing movement inspired by rural living and regaining contact with nature and the growing of food. An additional (but arguably temporary) initiator for this ideal are the restrictions that COVID-19 puts on urban lifestyles. When staying at home becomes the norm and social gatherings almost obsolete, a 40 m² apartment in the city centre with no outdoor space and study room suddenly loses much of its appeal.

2. Vertical Farming

Urban Agriculture

Over the years, multiple adaptations to these challenges have been developed, of which many can be accommodated under the term *Urban Agriculture*, which suggests a means to ensure a supply chain of locally produced, fresh food. Some implementations focus on the primary need of fresh food, while others focus on challenging what and how we consume (Borghini et al., 2020). These concepts range from rooftop gardens to automated plant factories *(fig. 3)*. Given the financial value of urban space, these concepts require exceptionally high productivity to remain economically viable (Lambin & Meyfroidt, 2011).

Fig. 3. Implementations of urban agriculture.

Plant Factory with Artificial Lighting (PFAL)

In 1999, Despommier coined the concept of *vertical farming*; growing crops vertically (on multiple stacked layers) as opposed to horizontally. Hydroponic systems (growing based on water instead of soil), lent themselves best for growing vertically and are thus the most adopted growing system for vertical farming (Kozai et al., 2020). Within the concept of vertical farming, different levels of control and automation exist. Ranging from vertical structures within a greenhouse using direct solar light, to closed systems with LED lights to enable photosynthesis. The latter systems, also termed Plant Factories with Artificial Lighting (PFAL), are designed to maximise production density, productivity and resource-use efficiency (Graamans et al., 2018; Kozai et al., 2019) *(fig. 4)*. This high level of productivity is achieved by adapting the interior climate to achieve uniform lighting, temperature and relative humidity through minimising the interaction with the exterior climate. Limiting this interaction can also benefit the efficient use of energy, water and CO_2 (Goto, 2012; Graamans et al., 2018).

Fig. 4. Examples of Plant Factories with Artificial Lighting (PFAL); Aerofarms *(left)*, Certhon *(right)*.

PFALs have the following potential advantages over conventional production systems such as greenhouse structures and open-field production (Kozai et al., 2019):

- Not location bound because no solar light and soil is needed
- The growing process is not affected by outside conditions such as extreme weather
- Year round production and could reach over 100 times the production per land area of field production
- Enabling optimal growth conditions results in enhanced crop quality
- Production is pesticide-free and does not require washing
- Produce has a longer shelf life, due to low bacterial loads
- Reduced transportation when building PFALs near urban areas
- High resource use efficiency such as water, CO_2 and fertilizer with minimal emissions to the outside environment.

3. Problem Statement

Though the advantages are plentiful, there also are some disadvantages of PFALs, in which a distinction can be made between mechanical and managerial. The most obvious disadvantage of a PFAL is the energy requirement predominantly from artificial lighting(LEDs) and HVAC systems (vapour and air removal) (Graamans et al., 2017). As for managerial bottlenecks; labour costs in PFALs that have relatively little automation are often underestimated (de Oliveira et al., 2020; Liotta et al., 2017); lack of adequate VF knowledge and education; inefficient workflow and inadequate ergonomic design considerations (Liotta et al., 2017).

Besides these bottlenecks, there also exists another more social, architectural problem. When approaching PFALs from a perspective of production quality and efficiency, PFALs are at risk of materialising as a closed box *(fig. 5)*. This would result in a paradox; food production is returning near the vicinity of the consumer, but instead of the consumer regaining their dilapidated connection with food, as addressed by Steel (2013), they remain just as oblivious about the process by which their food is produced as when it was acquired from across the globe.

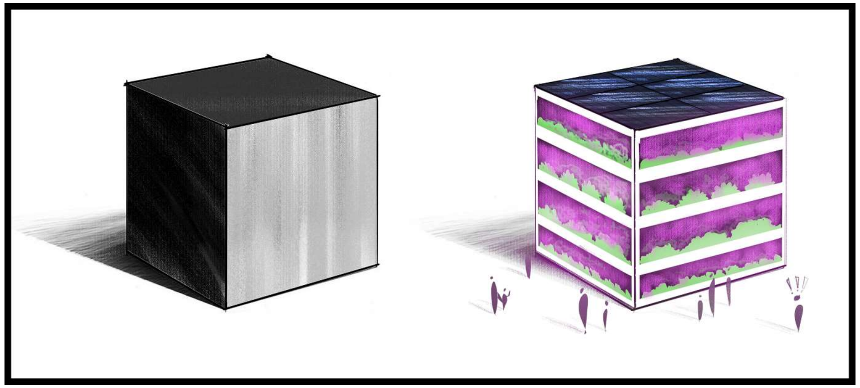


Fig. 5. Plant Factories with Artificial Lighting (PFAL) are at risk of being architecturally translated as a closed box *(left)*. Instead PFAL's should open up to the consumer allowing them to reconnect with (the production of) their food *(right)*.

METHODOLOGY

1. Problem Definition, Objective & Research Questions

Problem Definition
Studying both conceptual and realised PFAL projects, a two-way distinction is noticeable in the perspective from which these projects are approached; *technological fix* and *anthropological fix* (Borghini et al., 2020). The technological being a focus on producing fresh food by using technological advancements to achieve optimal production quality and efficiency in an economically viable manner. The anthropological being a focus on social qualities; the wellbeing of involved actors (e.g., consumers, residents and workers), by challenging the paradigm around food(production) (Steel, 2013).

> Chances are none of the fanciful, futuristic "Jetsons" vertical farms that you'll find on Google Images won't be built, as they're not considering the reality of farming on a commercial scale. Many of these designs are proposed by architects and designers, not the farmers themselves. (Despommier, 2016, Q&A)

Besides architectural designs that fulfil neither the technological nor anthropological aim, Despommier addresses that designs striving for the anthropological fix often seem to lack the technical and biological know-how needed to realise an economically viable project. An accusation that if true, they can hardly be blamed for, as literature is still scarcely available on acquiring the technological know-how from an architectural perspective. On the other side of the spectrum, large scale agriculture is almost never integrated with the urban fabric and even in e.g. *Het Westland* (The Netherlands), what can be considered to be urban agriculture because of its geographical orientation in *De Randstad*, is a world of its own unknown to city-dwellers. The consumer becomes less and less aware of what they are eating, where it comes from and how it is grown.
Utilising merely the technological advancements to meet the demand for fresh food, will be either not sufficient or simply a very inefficient way of adapting to future food challenges (Borghini et al., 2020; Steel, 2013). With the emerging method of growing in PFALs disrupting the traditional market of agriculture, there lies an opportunity to tackle this problem right from the get-go. Optimise the efficiency of vertical farming facilities while truly integrating them into the urban fabric; providing not only the product of fresh produce but also enable the consumer to experience the growing process and reconnect with their food beyond the level of it being a mere calory and nutrient input.

Research Phase
When a PFAL is not economically viable it will either go bankrupt or not be built at all, an example being The New Farm in The Hague (Groente Nieuws, 2019). Thus, starting from the notion that the design should contain a high degree of production quality and efficiency, *what freedom does the architect have to incorporate anthropological qualities into the design*? Insufficient literary works are available on PFALs approached from an architectural perspective addressing the dynamic between these technological and anthropological paradigms. To shed light on this dynamic, the primary research question of this research is as follows:

*Which **factors** that enable **optimal production quality and efficiency**, are **relevant for architects**, when **designing Building Integrated PFALs**?*

Design Phase
During the Design Phase of the project, the focus is shifting from a non-location bound understanding of PFAL design, towards exploring the potentials of the architectural integration of PFALs in De Randstad (The Netherlands). With as guiding objective an elegant and socially inclusive architectural design of a Building Integrated PFAL, using the know-how acquired from the research phase to retain production quality and efficiency. This design strives to combine: efficient production of high quality fresh food (economic & sustainable process); interaction between the consumer and their food's production process; aesthetic enhancement of the site & an enlightened experience for its spatial users.

The relation between research and design can be described as a puzzle which can be put together in multiple configurations, but not all of those configurations result in an equally complete solution. The Research Phase provides the pieces and the Design Phase explores the configurations. Let Plant Factories with Artificial Lighting become an elegant and socially inclusive solution, instead of a closed box.

2. Research Method

Research Phase
Architecture is a multidisciplinary practise, with intuition playing a significant role in the creative process (van Dooren, 2020). This makes determining the exact relevancy of a (vertical farming related) aspect a difficult and subjective discourse. Using information acquired from existing literature and discussions with experts in the field, multiple aspects that are potentially relevant for an architect designing building integrated PFALs were identified to form a basis for this research.
During further literature based research, these were adjusted to eventually form the factors and primary categories as displayed in figure 6. The applicability of each factor will differ per project, this is up to the architect and other stakeholders to identify. Additionally, studies in the Design Phase reflect on applicability of the factor list, allowing for potential iterations during this phase.

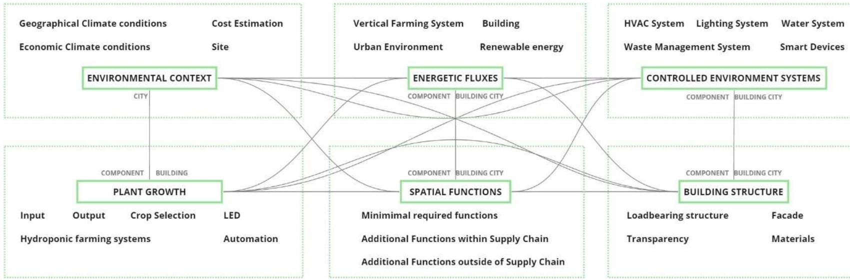


Fig. 6. Factors ordered in six primary categories: environmental context, energetic fluxes, controlled environment systems, plant growth, spatial functions and building structure.

Resulting in a factor list that qualifies the aspects which influence optimal production quality and efficiency. Identifying where the architect has room for interpretation, to integrate social and aesthetic qualities into the design, with minimal compromise on production quality and efficiency.

To improve the legibility, all factors are described using the same layout structure *(fig. 7)*. Depending on the nature of the factor (e.g.; building structure or energetic fluxes), rule of thumb equations are included to help the decision-making process and determine the applicability of the factor for a specific context. Besides taking into account scientific results which are validated in the past, designing with these novel technologies also benefits from and understanding of technological developments in the near future (1-10y).

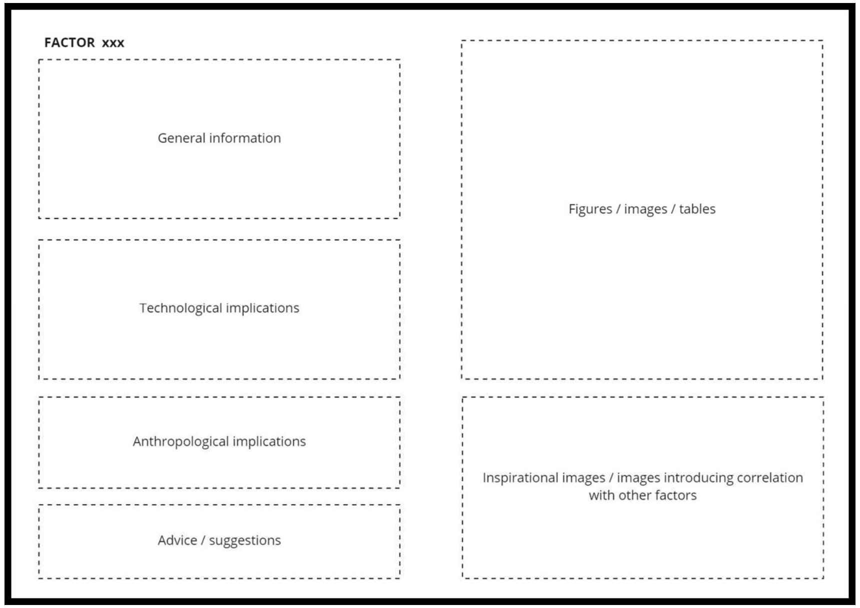
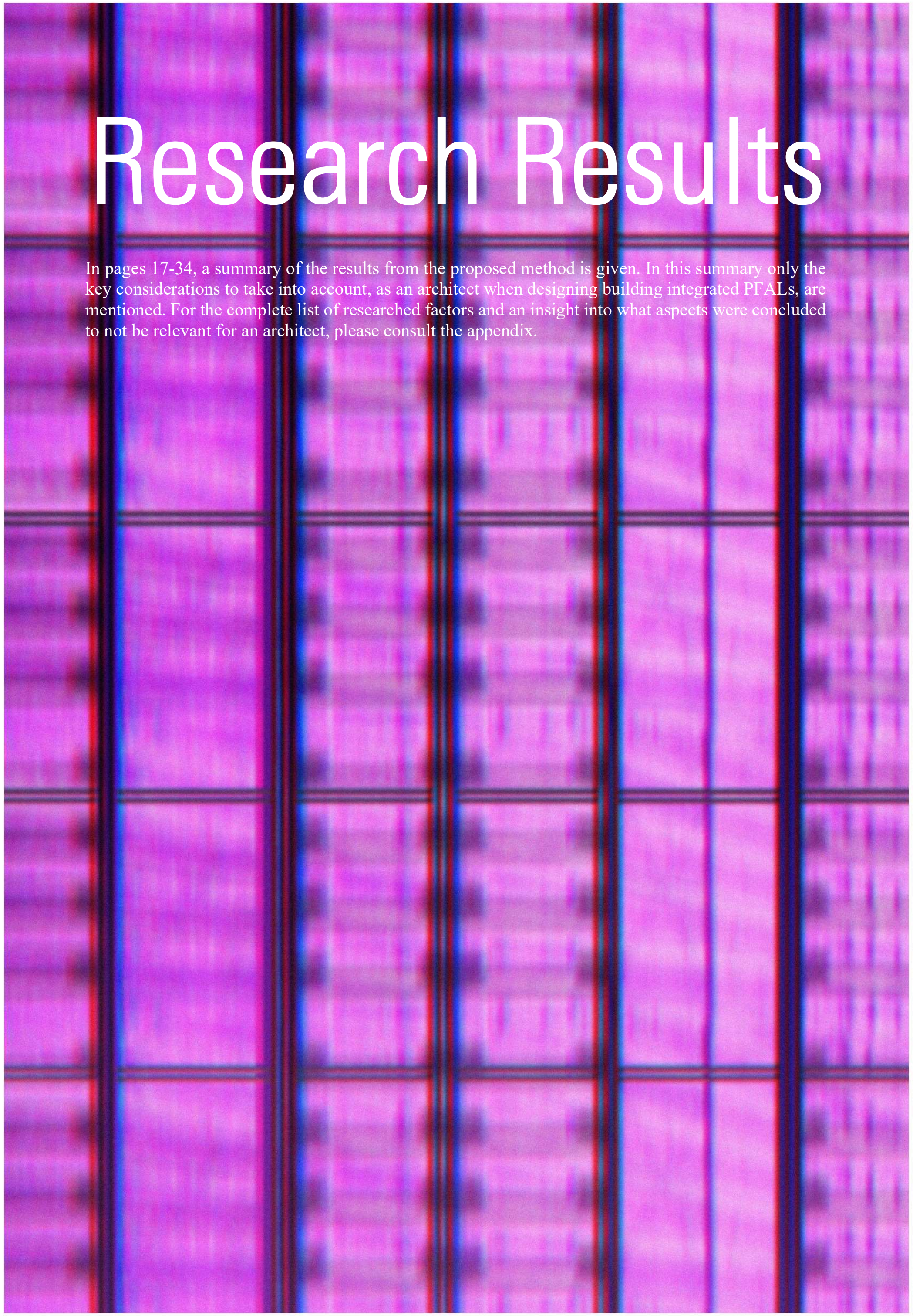


Fig 7. Each factor is elaborated according to this layout.

The research results are concluded with an overview of the most important and/or fascinating findings.



Research Results

In pages 17-34, a summary of the results from the proposed method is given. In this summary only the key considerations to take into account, as an architect when designing building integrated PFALs, are mentioned. For the complete list of researched factors and an insight into what aspects were concluded to not be relevant for an architect, please consult the appendix.

1.1 Geographical Climate Conditions

Geographical locations that suit PFALs best are those with extreme climate conditions because compared to open-field or greenhouse agriculture the growing process is much less impacted by these external climatic factors. Geographical climate conditions such as temperature, rainfall, humidity, weather extremes and average solar radiation impact the type of PFAL and its ability to open up towards exterior spaces without increasing energy demands. In fact, opening up parts of the PFAL can benefit the total energy demand by reducing internal heat loads in most climates (see 4.1 & 6.2). The reason why many PFALs are completely closed is out of (managerial) simplicity, not because of optimal efficiency (Graamans et al., 2020). To obtain a broad idea which locations lend themselves best for PFAL growing, the prominent conditions of water scarcity and relative electricity efficiency are plotted on a world map *(fig. 8)*.

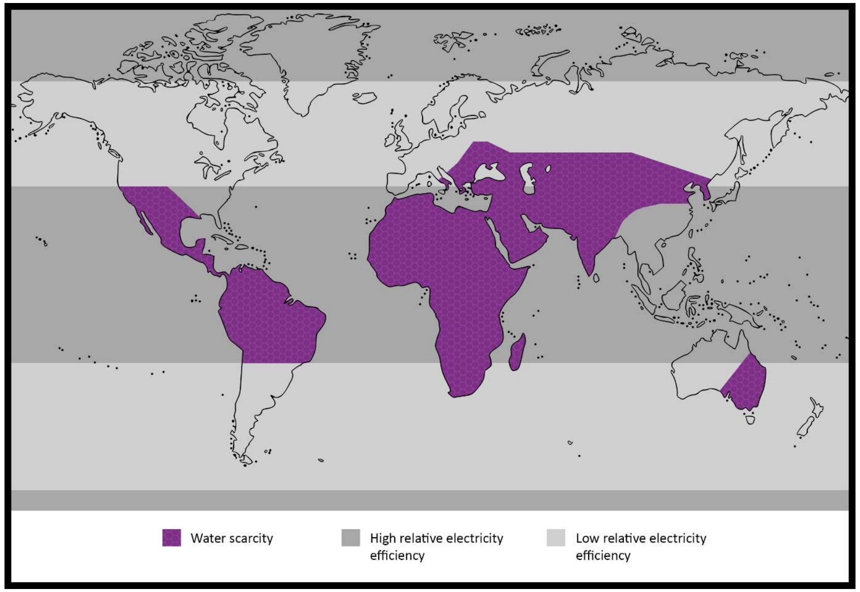


Fig 8. World map displaying advantageous locations for PFALs according to relative electricity use and water scarcity. Adapted from Graamans et al. (2018).

1.2 Economic Climate Conditions

Major components in evaluating the economic viability of a PFAL are its location and local supply chain. Extreme climate conditions and a high urban density are two primary criteria. If there is a high import ratio of certain crops, plant factories have a high potential for being economically viable for these crop types. Import is expensive and unsustainable, thus weighing up against the higher energy costs of plant factories. Understanding the local supply chain *(fig. 9)* will help find potentials to shorten the chain through (partial) integration of multiple supply entities into the PFAL building e.g., a supermarket or restaurant (see 5.2).

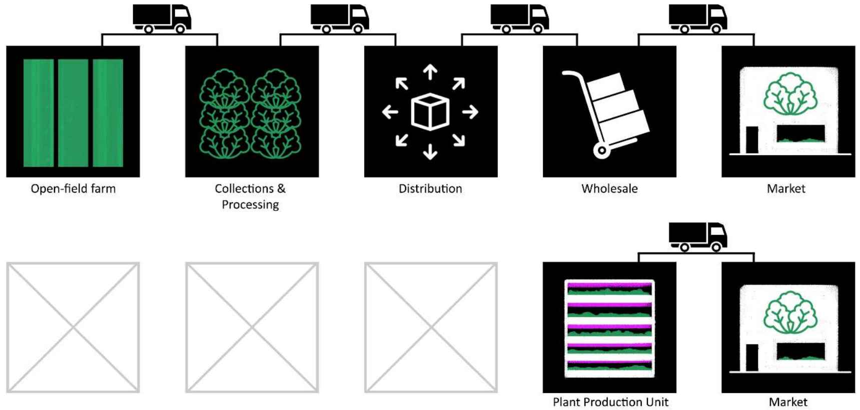


Fig. 9. Difference in supply chain between traditional open-field & PFAL. Adapted from PlantLab (2019).

1.3 Cost Estimation

Kozai et al. (2020) identify labour (26%), electricity (28%) and depreciation (23%) to be the main operational cost factors of plant factories. Long-term labour costs can be reduced by automation (see 2.4), electricity by increasing the energy efficiency of the PFAL and depreciation potentially by using circular materials.

When opening up the proposed closed box that are PFALs, maintain a pathogen free environment as it is the main characteristic consumers are willing to pay extra for when buying bagged lettuce (Dool, 2018).

1.4 Site

To efficiently reconnect city-dwellers with the natural process of growing food, determine the possibilities residents or pedestrians have to connect with this process that are already in place. Then, integrate functions into the space that are lacking or could be improved. Similarly, consumers are unlikely to go outside of their residential building to acquire a single crop of lettuce, they are more likely to prefer a supermarket at which they can acquire a larger variety of foods. Thus, either develop a PFAL within the residential building or with supermarkets and restaurants which offer more than just a limited variety of vegetables.

2.1.1 Crop Properties & Selection | Basics of Plant Growth Input

Properties of plant growth indirectly influence the architectural design of a PFAL. The demands for illumination and HVAC, and therefore also the freedom an architect has in designing with these systems, are results from plant growth. Using this reasoning, these are the most impactful aspects of plant growth for the architectural design of a building integrated PFAL:

Light (Photosynthetically Active Radiation, PAR *(fig. 10)***):** Both light quantity (intensity/ concentration of sunlight) and light quality (wavelength of light) influence plant growth. The process of photosynthesis uses predominantly red and blue light (Kusuma et al., 2020).

- Blue photons — inhibit cell expansion
- Red photons — efficient photosynthesis
- Green photons — facilitate human vision
- Far-red photons — enhance cell expansion

Light duration: The amount of time a plant is exposed to light (photoperiod) and the amount it is not exposed to light is defined as the light-dark cycle. For instance, lettuce resides best under a 16h/2h light-dark cycle (Hiroki et al., 2014).

Temperature: Temperature influences photosynthesis, transpiration, respiration, germination, and flowering. Temperature increase (to a certain point) increases photosynthesis, transpiration and respiration. In combination with light duration it also affects the growth from vegetative (leafy) to reproductive (flowering).
Germination: Germination temperature varies per species.
- Cool-season: spinach, radish, lettuce = 15°C / 19°C (lettuce germination optimum)
- Warm-season: tomato = 21°C / 27°C (tomato germination optimum)

Crop quality: Low temperatures reduce energy use and increase sugar storage. High temperatures cause bitter lettuce.
Photosynthesis and respiration: Thermoperiod = daily temperature change. Plants grow best with a daytime temperature +/- 10/15 °C higher than the night-time temperature.
Water and Humidity: Water is:
- Primary component in photosynthesis and respiration
- Responsible for turgor pressure in cells (fullness and firmness of plant tissue)
- Cooling leaves by evaporating from leaf tissue during transpiration
- A solvent for minerals and carbohydrates moving through the plant
- The medium in which most biochemical reactions take place

Plant Nutrition: Plant growth is influenced by up to 20 macro- and micronutrients. The concentration of nutrients differs per plant and desired growth. The macronutrients are listed below.
Found in air:

Carbon (C)	**Hydrogen (H)**	**Oxygen (O)**

Found in soil or hydroponics substrate (98% absorbed through soil-water solution, 2% extracted through soil-particles):

Nitrogen (N)	**Potassium (K)**	**Magnesium (Mg)**
Calcium (Ca)	**Phosphorus (P)**	**Sulphur (S)**

Nutrient absorption: Anything that reduces sugar production in leaves lowers nutrient absorption. Thus, if a plant is under stress because of low light or extreme temperatures, nutrient deficiency may develop. Plants also absorb different nutrients as flower buds begin to develop than they do during periods of rapid vegetative growth.

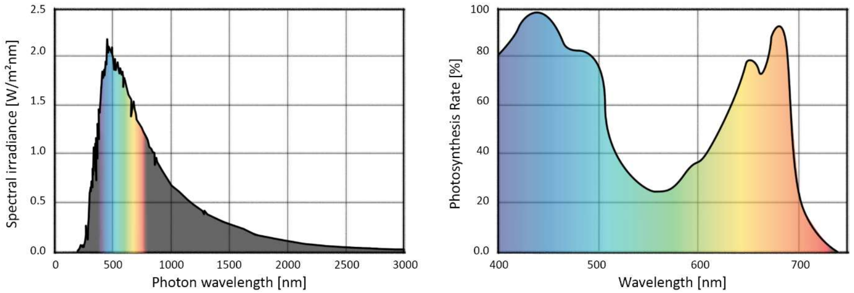


Fig. 10. PAR in relation to the solar spectrum *(left)* and PAR in relation to the photosynthesis rate *(right)*. Adapted from McCree (1981).

2.1.2 Crop Properties & Selection | Basics of Plant Growth OUTPUT

The primary result of plant growth in PFALs and the reason for their existence is; edible mass. For example hydroponic lettuce production was calculated to result in a yield of 41 lettuce heads per square meters a year, or ±SD 6.1 kg/m²/y of which only 5% (the roots) are non-edible mass (Barbosa et al., 2015).
Besides edible mass, there are other components that result from of the plant processes taking place within a PFAL: non-edible plant mass (see 3.4); transpiration and evaporation (see 3.1 & 4.1); unabsorbed water and nutrients (these can be recirculated).

2.1.3 Crop Properties & Selection | Vertically Farmed Crops

Not all plants enable a viable business case when grown in a PFAL. Though a large part of its viability depends on the technological developments, there are some plant-aspects that lend themselves better to growing in a vertical system *(fig. 11)*:

- **Short production cycle** *(10-30 days growth cycle)*: the more cycles within a period of time, the lower the relative energy costs per crop.
- **High harvestable yield** *(>80% fresh weight can be sold)*: the larger the portion of the crop that can be sold, the lower the relative energy costs per crop.
- **Short stature** *(<50cm including root height)*: more plants per cubic meter. The height of the produce also determines the amount of trays the VF system can stack within a certain building height.
- **Year-round demand**: one of the strengths of an indoor farm is the ability to grow year-round, naturally this requires a year-round demand of the produce in order to use the farm's potential.
- **Limited labour**: lower cost.
- **Perishable**: crops with a short shelf life benefit from growing close to the consumer, which can be done within vertical farms.
- **High value**: the production cost of indoor crops is higher, this requires that the crop grown is of high value in order to be profitable.
- **Value added**: can the acquired quality of crops grown indoors be sold for a higher price? This value can be added by for example production security or reliable harvest (periods).

Fig 11. A selection of phase 1 crops: Looseleaf Lettuce, Dwarfed Kale, Basil Genovese and Swiss Chard.

2.2 Hydroponic Farming Systems

Any vertical farm and especially PFALs use a hydroponic system to grow their crops. A hydroponic system does not require soil to grow in, but instead uses nutrient solutions distributed through and aqueous solvent. These systems are a lot more water efficient than open-field or greenhouse systems, because the water that is not used does not disappear into the earth, it can be recirculated. Thus, almost all the water used in the system besides evapotranspiration goes into the plants and even evapotranspiration could be captured and recirculated. It also decreases the use of fertilizers or pesticides. There are various variations of these hydroponic systems, an overview of the basic types is provided *(fig. 12)* (Al-Kodmany, 2018; Graamans, 2015; Sharma et al., 2018):

- **Nutrient Film Technique (NFT):** Nutrient solution is pumped to the highest point, then guided by gravity through channels on which the plants are situated.
- **Aeroponics:** Spraying the roots of plants with mist and/or nutrient solutions, requiring less water compared to other hydroponic systems.
- **Ebb and Flow:** An aggregate is used to keep the roots in place in an interior rooting bed, standing in a watertight exterior bed. Water and nutrient solution are pumped into the exterior bed and through gravity the exterior bed gets emptied again. This process occurs multiple times a day like ebb and flow of the sea.
- **Deep Flow Technique (DFT):** Floating rafts carrying the plants within a basin of water and nutrient solution.
- **Drip System:** water and nutrient solution are directly dripped onto the plants, with excess being captured in an external bed.
- **Aquaponics:** Integrates aquaculture (fish farming) with hydroponics. Creating a symbiotic relationship between plants and fish by using the nutrient-rich waste materials from fish tanks to fertilise the crops and the crops filter the water for the fish to live in. The system provides great potential, but in practise is difficult to maintain.

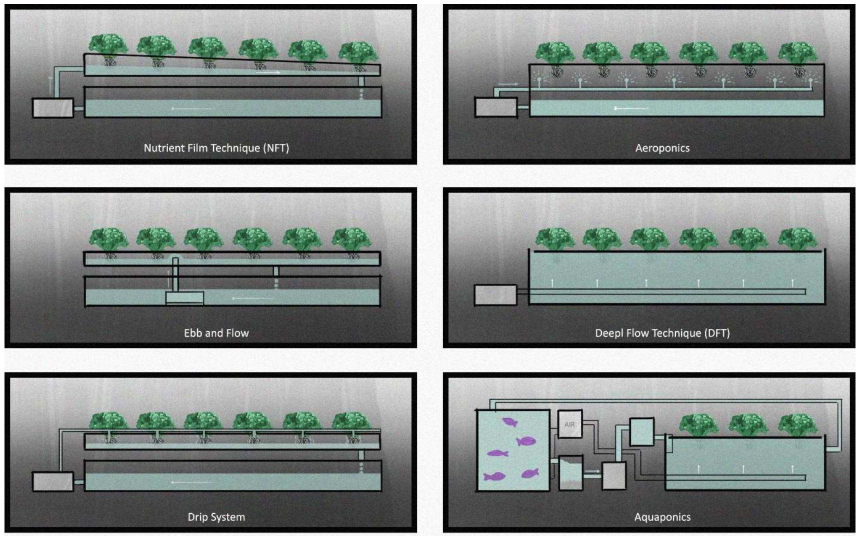


Fig. 12. Overview of hydroponic systems.

2.3 Light-Emitting Diode (LED)

A PFAL uses LEDs to enable full control of the light irradiation that is used for plant growth. The LEDs have a major impact on the efficiency of the growth process, aesthetic of the facility and energy cost of the facility. As addressed in 2.1.1, plants predominantly use red and blue light to grow. Thus, the LEDs within a PFAL are also predominantly red and blue. With only red and blue LEDs, plants appear as black or dark purple because all the light is absorbed *(fig. 13)*. This drastically alters the conventional paradigm of most consumers about plants.

To adhere to both the day-night cycle of the plants as well as the aesthetic of the PFAL and energy efficiency, these dark periods can be divided over multiple compartments (see 3.2 & 4.1). The slight inefficiency by light transmitted outwards on the sides of the trays is determined as minimal and more than made up for by visibility for involved actors (e.g., workers, consumers, residents and visitors).

Fig. 13. Plants (basil) appear as dark purple because almost all light is absorbed.

2.4 Automation

Currently (2020), most handling operations are conducted manually if the daily production capacity of leafy greens is <5000 heads per day. In most cases, above 10.000 h/d, operations are semi- or fully automated *(fig. 14)*. This includes:

> seeding, uploading, unloading, and transporting of culture panels to and from the tiers, weighing of leaf greens, packing the harvested produce in plastic bags, labelling the plastic bags containing leaf greens, packing the plastic bags into container boxes, labelling the container boxes, and wrapping the boxes before cooling. (Kozai et al., 2020, p. 262)

Operations that are difficult to fully automate include trimming damaged leaves and packing plastic bags into boxes. It can therefore be concluded that a major portion of PFALs will become automated, but in small scale factories workers remain physically present.

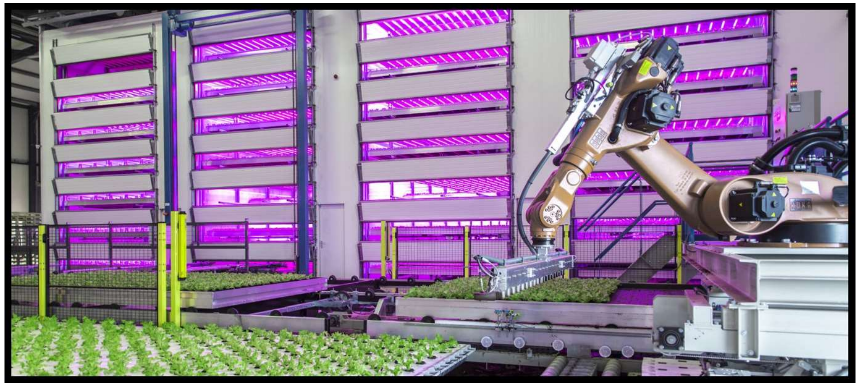


Fig. 14. Automated PFAL developed by Certhon & Signify.

3.1 HVAC System

The optimal growing temperature and humidity levels vary per plant. Generally, growers choose to recirculate all of the supplied air not introducing any additional fresh air because the plants consume CO_2 (Strum, 2019). Instead of introducing 'fresh air' into the mix CO_2 is often added to provide the optimal concentrations for growing (obtaining levels around 1200p/m CO_2 (Graamans, 2015)).
During the day-time of the cycle, there are significant heat loads from the LEDs and the resulting evapotranspiration (latent heat) from the plants. During this time the HVAC system must provide both sensible cooling and dehumidification. During the night-time period most of the sensible heat loads (e.g. LEDs) disappear but plant transpiration to some extent remains present. Thus, during night-time the HVAC system is required to necessitate dehumidification without sensible cooling (Strum, 2019). It can also occur that the plants continue to transpire, cooling the space around them resulting in the need for heating. The Rc-value of the building envelope greatly impacts this need for heating, as well as the external climate conditions (see 5.2). "Indoor agriculture HVAC systems must be designed for loads and operation that is very different when compared to comfort cooling for humans" (Strum, 2019, p.4). The system generates plenty of excess latent and sensible heat which should be utilised in e.g. the heating of residential spaces during night-time. In addition, look to meet the additional CO_2 demand by harnessing excess CO_2 from surrounding infrastructure.

3.2 Illumination System

The positioning of the lighting system should be such that there exists minimal light bleed. Meaning, the horizontal farming trays in a closed system should be far enough from the LEDs so that it does not burn the crops but close enough so that there exists minimal light bleed (can be increased by reflective material on the sides). In spaces visible to involved actors, in particular external actors, light bleed enables the fascinating appearance of a PFAL and therefore outweighs the slight loss in efficiency (see 2.3, 6.2, 6.3).
The artificial light mix for plant growth varies per plant (both wavelength and light intensity [lux]). Because the light spectrum of these LEDs has a significant impact on the visual appearance of the plant factory, it is advised to discuss the types of plants and thus the light mix that will be used with the grower. To maintain familiarity to consumers and visitors, a presentation mode (white light) should be included for nearby trays.

Rule of thumb equation for estimating energy requirement for LEDs
(latent & sensible heat loads resulting from illumination system are estimated in 3.1)

Identify energy use of LED system/m1/h from the datasheet of the LED module that is used. Convert this to m² and determine the growth cycle (dark/light period*days).

ENERGY REQUIREMENT FOR ILLUMINATION	E*LEDmodule* [W/m²]
Philips Greenpower LED production module 3. 2020 *(see appendix 2.3)*	50

E*LEDmodule* [W/m²] * daily light period [h] * 365 days / 1000 = E*illumination* [kWh/m²/y]
E*illumination* [kWh/m²/y] * cultivation area [m²] = E*required.illumination* [kWh/y]

Example
*For cultivation area: 10.000m² 20*50m2 10 layers, lettuce. 21/3h light/dark period (see appendix 2.1.1)*
50 * 21 * 365 = **383 kWh/m²/y**
383 * 10000 = **38.300 kWh/y**

Note: LED tech is rapidly developing, thus the energy requirement for LEDs is likely to decrease significantly over the next couple years.

3.3 Water System

In Closed Environment Agriculture, the required water is drastically less compared to open-field farming. The reason being that the water which is not absorbed by the plants does not drain into the ground, but can be captured and recirculated. An additional but less significant option in terms of water waste, is capturing the excess water that resides in the air as vapour resulting from evapotranspiration. The higher the efficiency of the water system, the closer to a 1:1 ratio of water: plant mass (e.g. lettuce consists of 96% water). Looking beyond PFALs, some greenhouses utilise a natural filtering system in a parc-like environment, which could work similarly for PFAL-greenhouse combinations. This relatively simplistic way of filtering is enabled by the absence of pesticides.
Architectural design enable a visible as well as sensible experience of this closed loop water system. If the dripping noise is regulated in a calming way it strengthens the biophilic properties of the space (Browning et al., 2014).

3.4 Waste Management System

Two primary options for waste management within a PFAL are; aquaponics and burning biomass. In aquaponic systems, the fresh water that is not absorbed by plants is led into a fish tank. The waste from fishes contains nitrogen which is fed back into the water system for the plants *(fig. 15)*. Another means of using waste materials is through burning the non-edible biomass generating either E*heat* or E*electric* *(fig. 16)*. However, burning waste material for PFAL-grown crops to generate energy in the form of electricity was calculated to be insufficiently efficient to be viable for surface (growth) areas less than 5000m² (see appendix 3.4). When the latter is the case, process the non-edible biomass for composting at a nearby urban farm instead.

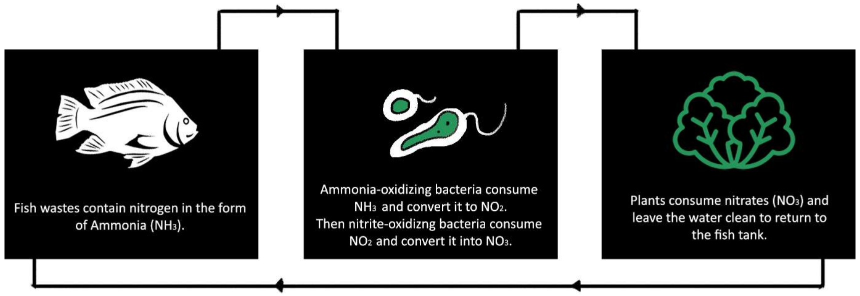


Fig. 15. Nitrogen Cycle of an aquaponic system. Adapted from RGJ (2020).

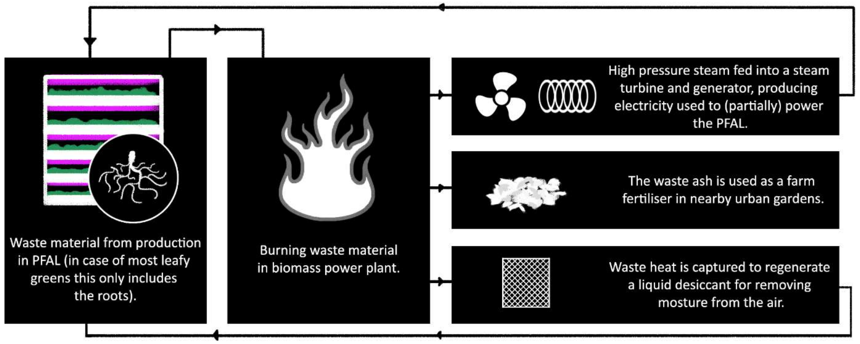


Fig. 16. Burning waste material in a biomass power plant to generate e.g. electricity. Adapted from Spark Architects (2014).

3.5 Smart devices

A major benefit of plant factories is the ability to control all aspects that influence plant growth; light intensity & duration, temperature, humidity, nutrient solutions, water etc. Once being able to control all those aspects two steps remain; gathering plant growth data to understand which plants need what kind of growth recipe, and following up on this data deciding when to use which recipe. There can be multiple recipes for ‘healthy’ plants but perhaps the grower requires a batch of leafy greens to be ready to harvest exactly in 20 days’ time for a holiday market peak, for which only one recipe is optimal. Step by step, this process looks as follows:

1. Create an environment which can be controlled
2. Gather data from sensors monitoring all relevant aspects within the PFAL
3. Understand the data, develop growth recipes
4. Decide which recipe to grow depending on market demand (forecasting)

Actively monitor the growing process to make minor adjustments whenever unexpected growth development occurs.

Acting on all this data is a skill that not many growers already poses and thus must first be learned. Particularly in the following years, PFAL structures can benefit from integrating an educational facility into the building. Educating the farmers of the future.

4.1 Energetic fluxes within the Vertical Farming System

Within the farming system there exist two main components that demand the majority of energy input: LEDs and HVAC (and depending on the level of automation, this can too become a major factor). The energy(heat) balance of the vertical farming module is (simplified) expressed as *(fig. 17):*

Rule of thumb equation for estimating energetic fluxes within the farming module

$$Qfacade + Qplant + Qlatent + Qequipment + QHVAC = 0$$

**For more complete equations to calculate energy fluxes, see;* Graamans et al., (2017); Li et al., (2020).

Graamans et al. (2017) calculated that a single crop of lettuce (average fresh weight 289 g) requires approximately 7.57 kWh*Electric* to grow, opposed to approximately only 1.55 kWh*Electric* in a greenhouse situated in The Netherlands (a requirement that will decrease in the coming years due to a increase in LED efficiency (see appendix 2.3 & 3.2)).

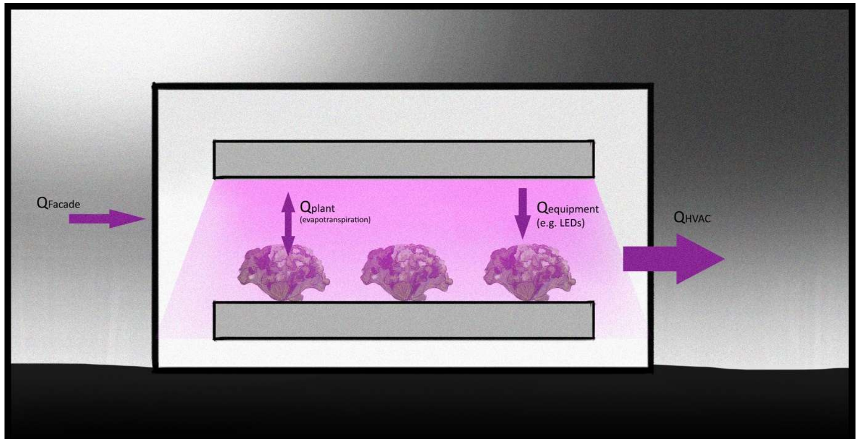


Fig 17. Plant factory energy (heat) balance. Adapted from Graamans et al. (2017).

4.2 Energetic Fluxes within the Building

Estimating the energetic fluxes within a building, without taking into regard potential other functions besides the PFAL can be done as follows:

Rule of thumb equation for estimating energy fluxes within the building

Use the equations from 3.4, 4.1 & 4.4 to estimate the energy requirement within the building

$$Eoperational + Ewaste + Esolar = \text{Energetic fluxes within the building [kWh/y]}$$

These can be expressed in e.g.; W/m² or kWh/y. Note that this equation combines both thermal and electrical energy loads.

Utilising the excess heat loads is a key component of the energy efficiency in the architectural design of building integrated PFAL *(fig. 18)*. Suggestions how this can be achieved are addressed following two building typologies; residential and supermarkets.

Residences

Excess heat from the farming unit can be used for underfloor heating. Feed CO_2 which is produced in residences into the PFAL for photosynthesis during the light period to produce O_2, which is fed back into the living or sleeping compartment.

For example, during the day obtain O_2 rich air by opening up a window. During the night, obtain O_2 rich air through setting the light period during the night producing O_2 for the sleeping quarters.

Supermarket

A lot of CO_2 is produced during the opening hours, which can be fed into the farming system (the light period is during the day because that is when consumers can experience the farm). Likely, both the supermarket and vertical farm produce excess heat, thus requiring to look beyond the building scale to distribute this heat *(see 4.3)*.

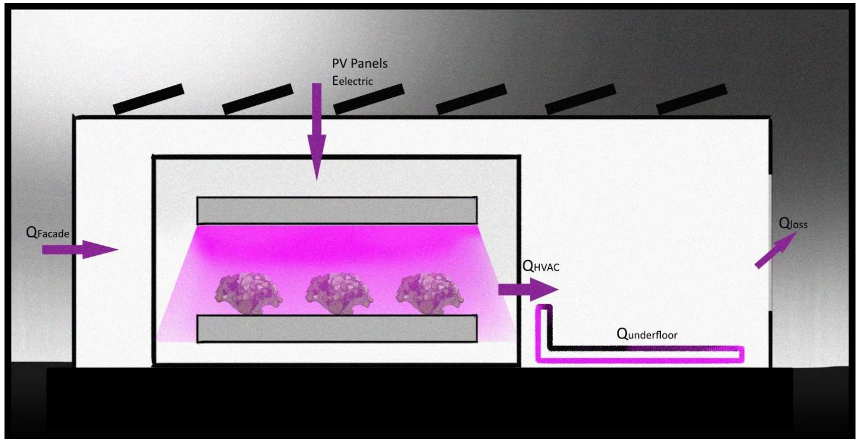


Fig 18. Example of energetic fluxes within a building with PFAL. Note: to simplify the figure, additional energy sources such as geothermal heat pump are excluded.

4.3 Energetic Fluxes within the Urban Environment

When closing the energy system within the building does not suffice, this does not mean energy (e.g. in the form of heat) has to be wasted. Nearby urban functions may lend themselves for excess energy utilisation *(fig. 19)*. If designing for a building block, the energetic fluxes are a factor to be aware of when deciding on which functions should be present in this building block. It can greatly benefit the sustainable and economic qualities of the project.

The more the urban system starts to make use of renewable energy sources such as wind and solar, the higher the extremes of energy availability. There is not always wind nor solar thus at peak moments there will be an energy abundance and at lows an energy demand difficult to provide. The obvious solution is large battery plants. What if PFALs can replace those batteries? When there is an energy abundance PFALs trigger the light period and when there is an energy demand PFALs trigger the dark period. This may result in slightly less optimal growing conditions, but it may very well be worth it looking at the energy costs.

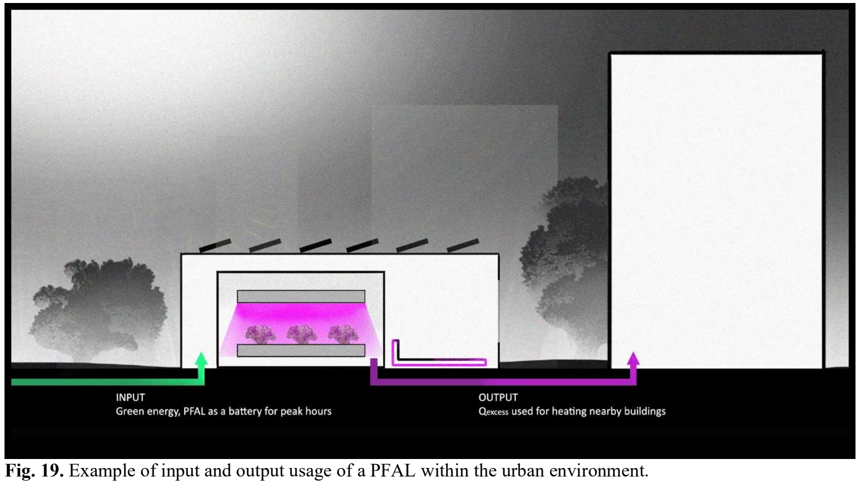


Fig. 19. Example of input and output usage of a PFAL within the urban environment.

4.4 Renewable Energy Sources (Specifically Solar)

The most prominent, building integrated, renewable energy sources for a PFAL are: solar energy, a geothermal heat pump and biomass (*see 3.4)*. Additional sources could apply for project-specific cases. For harnessing solar energy through PV panels, the following rule of thumb equation estimates the energy gain from these panels:

Rule of thumb equation for estimating energy gain from Photovoltaic Panels

1. Determine PV panel kWh/m²/y for the location of the PFAL. This usually comes with the datasheet, else using 170 kWh/m²/y will suffice for a rule of thumb calculation.
2. Note that this efficiency will quickly improve, thus look for yearly updates on kWh/m².

PV panel [kWh/m²/y] * Rooftop surface area [m²] = E*solar* [kWh/y]

Example

PV panel 170 kWh/m²/y & Rooftop area 1000m².
170 * 1000 = **170.000 kWh/y**

Commercially, the maximum efficiency of PV panels lies at 23%, using a PN junction. The *Shockley-Queisser limit* refers to the calculation of the maximum theoretical efficiency of a solar cell made from such a PN junction. The calculation places maximum solar conversion efficiency around 33.7% assuming a single PN junction with a band gap of 1.4 eV.
Incorporating e.g., solar energy and geothermal heat pumps early on allows for those systems to be more than a means to obtain energy but can also provide aesthetic and wellbeing benefits.
If the PV panels are placed in a visible location and/or angle, the visual appearance becomes a significant aspect of decision making. Advancements are being made that allow for coloured or patterned PV panels *(fig. 20)*, the drawback is a slight loss in efficiency.

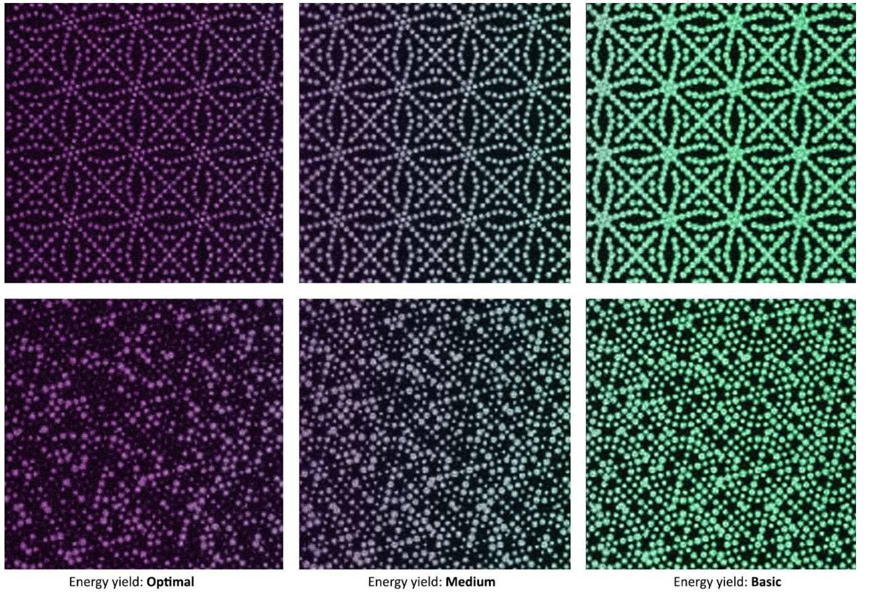


Fig. 20. Variety of PV patterns and colours. Adapted from Solar Visuals (2020).

5.1 Minimal required functions (to enable the VF system)

A plant factory consists of more than merely the CEA system. The following spatial functions are required for realising an efficient plant factory (Deutches Zentrum fur Luft- und Raumfahrt, 2015; Kozai et al., 2020):

Culture rooms *(sterile, pathogen free environments (fig. 21))*

- **Cultivation room**: from seedling to harvest ready *(see 2.2)*.
- **Germination room**: from seed to seedling (similar to the cultivation room but on a smaller scale).

Operation rooms

- **Storage**: short-term cooled storage of packed produce.
- **Shipping room**: ready to be transported to next link in the supply chain.
- ***Packing****: if not included within the automated space of the VF system.*
- **Maintenance / technical / electrical space**: this is more extensive than residential or office buildings.
- **Changing room**: to change into disinfected clothes
- **Air shower & wash basin**: to decontaminate workers/visitors before entering.
- **Boot sole sterilization**
- **Data storage**: if not done in the cloud a protected space for data storage is required.
- **Administrative/ Managing office**: Operating system for understanding processed data and carrying out decisions based on this acquired data.
- **Rest room & Tea room**

Fig. 21. A worker wearing clean overalls, shoes, cap, mask and gloves in a Kyoto based vertical farm. From Triballeau, C. (2019).

5.2 Additional functions: Within Supply Chain

To strengthen both the economical as well as social strengths of the plant factory it can be advantageous to add functions that lie within the supply chain of whichever plants the farm is growing. By incorporating functions that reside towards the end of the supply chain, so closer to the consumer, the plant factory can capitalise on additional profits otherwise lost to external parties while at the same time shortening the gap between production process and consumption. Some additional functions that reside within the general supply chain of PFAL grown crops:

Additional functions within the supply chain

- **Office:** to manage the plant factory and/or external companies looking for an inspirational office location (within the agricultural sector).
- **Restaurant:** allow the guests to dine within the surroundings of where their diner is being produced. Enjoying extremely fresh produce while dining in an enlightened and exciting space of innovative food production.
- **Shop/supermarket:** sell directly to the consumer without having to transport at all *(fig. 22)*.
- **Distribution centre:** rather than integrating a distribution centre with the PFAL, integrate the PFAL with a distribution centre.
- **Livestock:** grow food for livestock (wheatgrass) to feed farm animals which can be allowed to roam free one an adjacent plane (e.g. Grōv Technologies).
- **Residences:** arguably with one food within the supply chain as it houses the end consumer. The best way to directly influence the consumers paradigm is by integrating a PFAL within their residence.
- *And so on…*

Fig. 22. Mini-PFAL in a supermarket. From Infarm (2020). Note: most of these supermarket integrations only keep the crops fresh as opposed to facilitating a complete growth cycle.

5.3 Additional functions: Outside of Supply Chain

The spatial functions that lie within the supply chain *(5.2)* are derived primarily from economic potentials. When approached from a social paradigm there are additional functions to be identified that can benefit the anthropological and perhaps also the economic success. A few additional functions outside of the supply chain are:

Additional functions outside of the supply chain

- **Education:** Teach the generation of the future about a future of farming. For the vertical farming market to expand, farmers with a different skillset to that of traditional farmers are required. Education centres can educate the farmers of the future.
- **Museum/experience centre:** Enhance the biophilic capacity and strengthening the enlightening potentials. Excite the public about vertical farming.
- **Research centre:** developing new technologies and plant recipes. The budget for research of produce is higher than the margin available for commercial purposes.
- **Residences:** arguably with one food within the supply chain as it houses the end consumer. The best way to directly influence the consumers paradigm is by integrating a PFAL within their residence.
- **Public garden:** for relaxation and reconnecting with nature *(fig. 23)*.
- *And so on…*

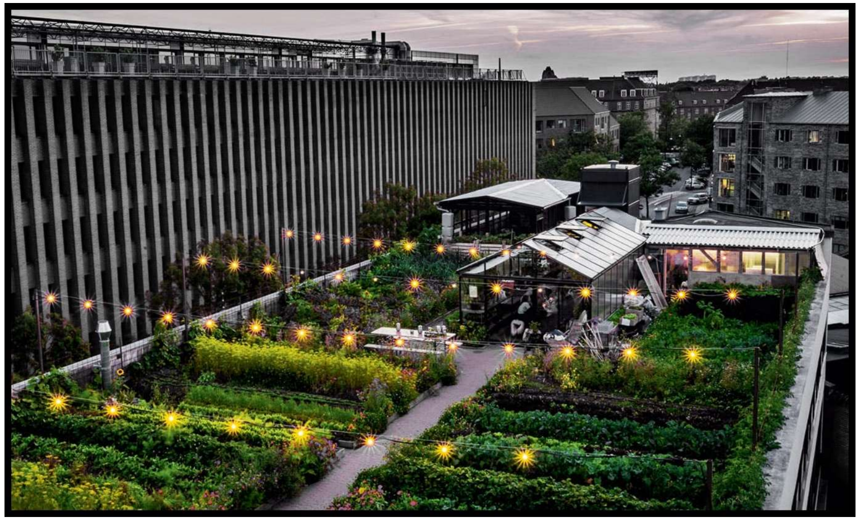


Fig 23. Rooftop garden, greenhouse and restaurant. From Østergro (2020).

6.1 Framing / Load-bearing Structure

For DFT, NFT & aeroponic systems or simply, plant factories with >100 m[2] cultivation floor area will mostly be made up of vertically stacked horizontal trays *(fig. 24)*. Resulting in a square/rectangular shape. In appendix 6.1 a table is provided showing spatial information of cultivation rooms within multiple PFALs. However, information of their structural loads [kN/m²] was not acquired having to conclude with that evidently, the farming system including its structure, water and crop weight is significant especially when exceeding heights of 4 m. Architecturally, the steel support structures within large PFALs are reminiscent of church naves with purple stained glass.

Fig. 24. Steel support structure for the hydroponic tray system. From RF Agriculture (2019).

6.2 Façade

Most PFAL that have been built between 2010 and 2020 have opaque façades and roofs, with a focus on achieving high Rc-values *(fig. 25)*. This allows for optimal control, with the drawback of a high energy demand from LEDs (both for PAR and resulting sensible heat load). In case of a transparent façade; natural lighting is not always present (e.g., cloudy days) nor can solar light fully penetrate to the centre of building structures, thus a combination of artificial illumination and solar radiation is required. To mediate the artificial illumination requirement, solar radiation must be monitored (including the additional heat loads that result from this).

Graamans et al. (2020) researched the potential of transparent façades, geometry and higher U-values versus the current preference of highly insulated walls. In climates such as The Netherlands and Sweden, higher wall to floor ratio's (W/F) result in an increase in total energy demand (caused by an additional heating demand). Whereas in warm climates such as United Arab Emirates, a larger façade surface area allows for an increase in sensible cooling through the façade, which is larger than the increase in heating. Thus in The Netherlands, PFALs with an opaque façade should be oriented horizontally and not vertically to minimize total energy demands.

For transparent facades, the opposite occurs in NL and SWE (higher W/F result in lower energy demands). This is caused by lower sensible cooling and a lower energy demand for LEDs, because the transparent façade allows direct solar radiation to hit the plants.

Though research is limited, it is suggested that a combination of an opaque roof with a high U-value and transparent facades provides (depending on location) benefits for both the total energy demand and visual appearances.

Fig. 25. Insulation panels; polyurethane foam and galvanized steel. Delta Construction (n.d.).

6.3 Transparency

Transparency can allow a connection between multiple spaces *(fig. 26).* The typology of the space can influence the preference for an opaque, semi-transparent or fully transparent wall. Four different transitional situations are discussed, in which a public space is defined as one which can be experienced by external actors by one or multiple senses:

- **Public exterior to public interior:** with the exterior and interior both being public spaces, it becomes possible to maximise the connection between exterior and interior. If the interior environment requires to remain sterile, a glass curtainwall is advised. The surface area of the transparent portion of the wall can be restricted when farmer wishes to retain easy control within the cultivation areas. An example of a design intervention with minimal heat and radiation transfer is a porthole allowing visitors or passers-by to peek into the PFAL.

- **Public exterior to private interior:** when the interior contains e.g. a research lab with intellectual property that is not yet sufficiently protected, these sections are required to remain closed off from the public. Similarly when protection from external factors in e.g. a germination room is vital to obtain a quality seedling. Ideally, such spaces are not situated directly next to public exterior spaces.
- **Public interior to private interior:** similar to the situation described above, with the difference that both spaces are already relatively controlled in terms of heat transfer and radiation. Thus reducing the impact on controllability and potential (in)efficiency of a cultivation room.
- **Private interior to private interior: i**n most cases, transparent facades can be implemented but the decision is made to use a cheaper opaque material instead. The reason being that e.g. workers are already familiar with the wonders of PFALs and if they wish to can simply enter the adjacent room.

Fig. 26. PFAL showcase inside Van Gelder Groente & Fruit. From Groentenieuws (2019).

6.4 Materials

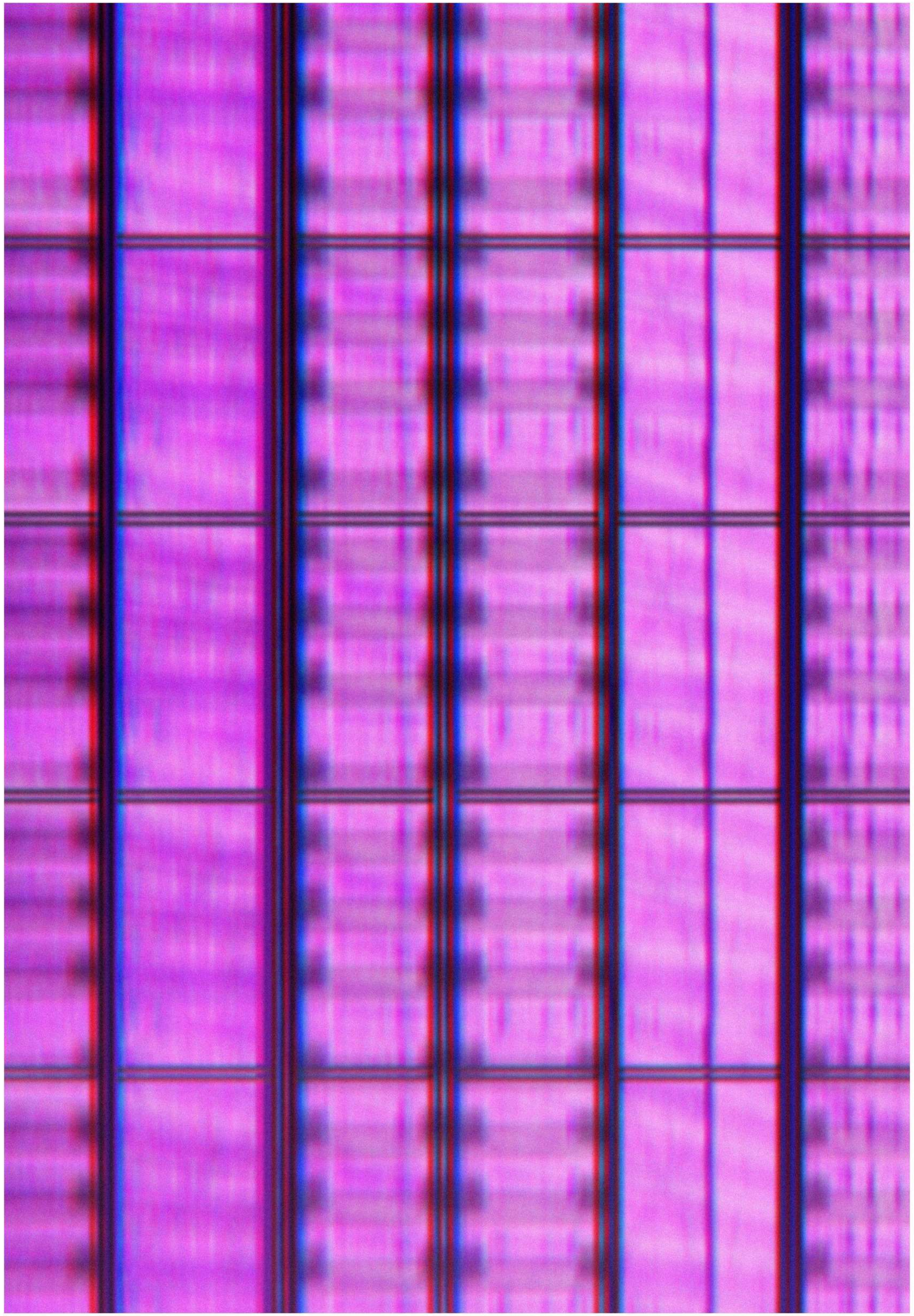
A comprehensive list of materials commonly occurrent in a PFAL *(fig. 27)*:

- **Glass**: enabling a visual connection between multiple spaces
- **Steel**: primary support structure (on small-scale PFALs plastics can also be used as structure for supporting the trays), often stainless
- **Polypropylene (virgin) plastics**: hydroponic trays and water systems
- **Polyvinyl Chloride plastics**: additional pipes for the hydroponic system
- **Concrete with epoxy coating**: flooring
- **Polyurethane foam:** insulation material.
- **Corrugated steel panels**: often used as prefab panels enclosing insulated foam.

Besides the conventional materials, these are three suggestions of which their properties appear to match architectural requirements of a building integrated PFAL as proposed in this project:

- Semi-transparent materials, allowing for flexibility in transparency e.g. switchable glass (see 6.3)
- Heat capturing material/transmitting materials to hold or transfer the excess heat to adjacent spaces
- Energy storing/generating materials such as solar glass and algae façades.

Fig. 27. Materials commonly occurrent in a PFAL.



CONCLUSIONS & DISCUSSION

1. Conclusions

Architecture is a multidisciplinary practise, with intuition playing a significant role in the creative process. This makes determining the exact relevancy of a PFAL-related aspect a difficult and often subjective discourse. For the relevancy of the described factors this implies that they can greatly vary per architect and per project. The following findings are deemed the most important, unexpected or fascinating and concluded to be (almost) without exception relevant for the architect to take into account when designing building integrated PFALs. All these findings are identified to fall under nine categories *(fig. 28)*. Though intended to address relevant factors for architects, there are also findings included which arguably are more applicable to project developers or farmers. The reason why these are included is that the latter findings can still indirectly impact an architects design choices, especially when the architect is involved early on in the project development.
The findings are therefore arranged by the project phase in which they are (generally) applicable and by being either directly or indirectly relevant for an architect when making design choices.

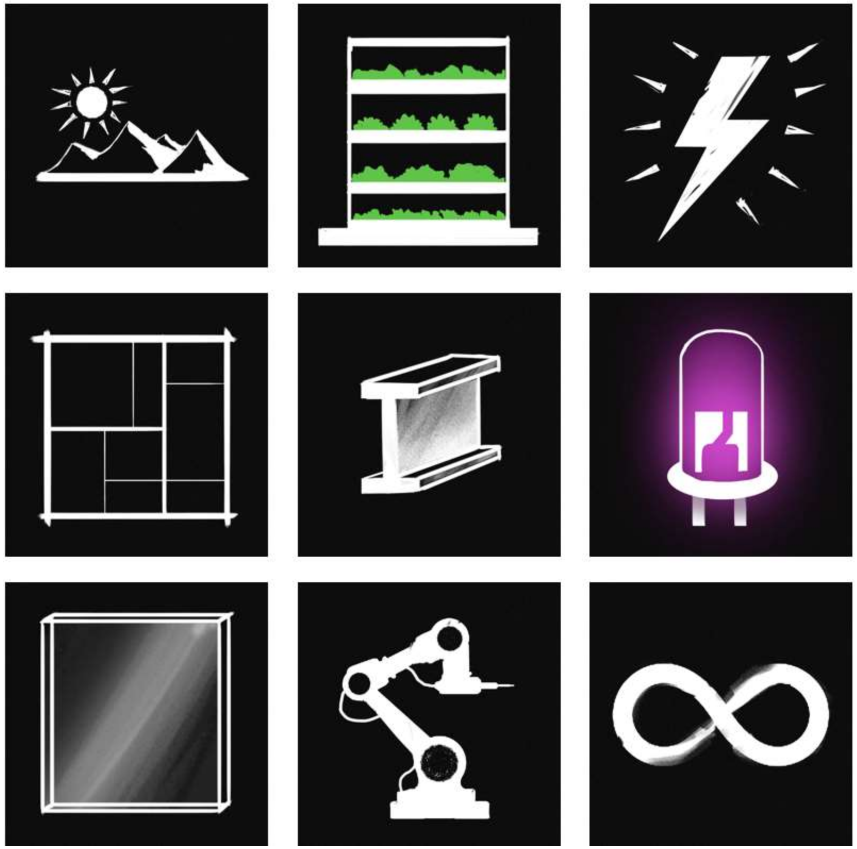


Fig. 28. Nine categories; Context, CEA System, Energetic Fluxes, Functions, Structure, Lighting System, Transparency, Automation, Closing the Loop.

INITIATION PHASE
INDIRECTLY RELEVANT

- Extreme climate conditions suit PFALs better because they increase their advantage over traditional techniques which are effected more by these external conditions (1.1).
- Commercial agriculture is a sector with tiny margins. When the project focusses around produce as the main source of income, the importance of economic decision making increases. However, additional functions (such as supermarkets, residences or museums) could alleviate this grip by adding (market) value (1.2, 5.2, 5.3).
- Understanding the supply chain and looking for ways to integrate multiple entities into a single building can benefit the economic qualities of the design and integration with the urban environment (1.2, 5.2).
- For who do you design the PFAL, most consumers gladly make use of the convenience of an all in one supermarket. Determine if you want to combat this trend (greengrocer) or work with it (integration with a supermarket) (1.4).

DRAFT DESIGN PHASE (SO)
DIRECTLY RELEVANT

- The functions within a PFAL are (5.1):
    - Culture rooms: Germination room, cultivation room.
    - Operation rooms: Packing, storage (cooled), shipping, maintenance, changing room, disinfection rooms (air shower, wash basin, boot sole sterilization), data storage, administrative office, rest room, tea room.
- Potential functions to integrate with a PFAL are:
  1. Within the supply chain e.g.: office, restaurant, shop/supermarket, distribution centre (5.2).
  2. Outside the supply chain e.g.: education, museum/experience centre, train station/underground transportation (5.3).
- Plants predominantly use blue and red photons for photosynthesis, hence blue and red LEDs are used. This results in the visual appearance of a purple haze within the cultivation area and the plants appearing almost black (since all the light is absorbed). In parts of the farm that are highly interacted with (in particular by external visitors or consumers) it is advised to include a '*presentation mode*' which displays the plants in white light, showing their lush green appearance (2.1.1, 2.3).
- When the floor area of the cultivation room exceeds around 200m² the culture areas are almost certain to consist of a stacked system of horizontal trays which allow for efficient automation. If the available space is smaller and manual labour is preferred, e.g. barrel shaped hydroponics can provide an interesting alternative (2.2).
- Water dripping from hydroponic systems contains biophilic qualities. Note that systems differ in how calming or constant this dripping is (2.2).
- In a moderate climate such as that of The Netherlands, it can be beneficial to integrate a greenhouse with the PFAL, especially when maximal control is not required. In particular non-leafy greens such as tomatoes can benefit from a combined system reducing the energy demand from LEDs (4.1).

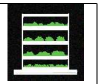
- Solar is a very potent energy source to utilise through photovoltaic panels on the roof of a PFAL, especially on a large-scale lightweight structure. In high density urban areas a rooftop garden or greenhouse provides benefits to users wellbeing which can outweigh energy gains. Naturally a combination would be ideal in situations that include rooftop greenhouses. The technology of photovoltaic panels is quickly improving, with 170 kWh/m²/y currently at the high end of commercial availability (4.4).
- With stacked trays as the most conventional structure for PFAL cultivation, aim to complement this structural aesthetic with that of the building structure. The structural loads that result from the framing differ significantly depending on design, automation and crop types (6.1).
- Increasing the transparency (of the façade) tends to negatively influence (6.2, 6.3):
  1. Controllability of the interior environment; internal climate, sterile environment. Though it does allow for potential energy saving.
  2. Trade secrets.
  Use transparent materials that show the visual appearance but maintain an interior sterile environment (e.g., glass). Differentiate between already protected IP (public) and research facilities (private).
- The different materials that resonate with a PFAL are studied during the Design Phase (6.3).

DRAFT DESIGN PHASE (SO)
INDIRECTLY RELEVANT

- The major cost components of a PFAL are; electricity 28% and labour 26%. But, the cost of electricity (e.g. LEDs) will greatly decrease in the next decennia and so could the cost of labour if automation is deployed. The question then becomes of a social nature, when and where jobs may be more beneficial to maintain (1.3, 2.3).
- The main characteristics that consumers are willing to pay extra for when buying bagged lettuce are zero contaminants and a longer shelf-life (1.3).
- Not all crops are economically compatible with growing vertically. Leafy greens, tomatoes (use a different system than the stacked layers described in this project) and strawberries are commercially grown, but e.g. grain requires too much energy to be commercially interesting with current technology standards (2.1.3).
- Sensors allow the farmer to monitor all aspects within a PFAL, but acting on all this data is a skill that must first be learned. Particularly in the following years, PFAL structures can benefit from integrating an educational facility into the building. Educating the farmers of the future (3.5).

FINAL DESIGN PHASE (VO)
DIRECTLY RELEVANT

- Indoor agriculture HVAC must be able to regulate much higher sensible (LEDs) and latent heat loads (evapotranspiration from crops) compared to comfort cooling for residential or office spaces. Re-using the excess heat accumulated by the system for e.g. underfloor heating in adjacent spaces is vital (3.1, 4.2, 4.3).

- To obtain CO_2 levels of around 1200 p/m, additional CO_2 is added to the airflow. The surrounding built environment is a potential supplier (if reducible to solely CO_2). It would allow CO_2 to be deducted from e.g. residential or office spaces, benefiting both the PFAL and external space (3.1).	
- The water intake is minimalised compared to open-field and greenhouse agriculture. There are greenhouses that utilise a natural filtering system in a parc-like environment, which could work similarly for PFAL-greenhouse combinations. This relatively simplistic way of filtering is enabled by the absence of pesticides (3.3).	

FINAL DESIGN PHASE (VO) *INDIRECTLY RELEVANT*	
- A potential use for the waste material (roots in case of lettuce) is burning its biomass for E*heat* or E*electric*. But note that e.g. burning biomass is not worthwhile when deployed on a small scale. If the surface (growth) area is <5000 m², instead look for composting at a nearby urban farm (2.1.2, 3.4).	
- Some advanced PFALs minimalize light bleed by closing the sides with reflective material. On sides that are visible to visitors or workers for check-ups, these sides should remain transparent, likely creating boxes which have one side left relatively transparent. The loss of PPFD efficiency is made up for by direct and indirect (economic and social) gains from consumers/visitors experiencing the PFAL (3.2, 2.3).	

2. Evaluation / Reflection

Due to the novelty of vertical farming and PFALs in particular, the available information on built projects to back up architectural assumptions is limited and involved companies are understandably reluctant to share information (protecting their IP). Partially, validation and iteration of the findings can occur during the Design Phase of this project, but a significant portion remains to be explored through actual built projects. Initially the aim was to develop a matrix that both quantifies and qualifies the factors relevant for an architect when designing PFALs in regards to maintaining production quality and efficiency. During the research it became clear that it is not helpful (at least during the research phase of this project) to attempt quantifying these factors using a Likert Scale (1-5), they are simply too different.

Overall, the Research Phase provided an useful overview and enables a fruitful Design Phase of this project.

3. Recommendations

User Guide

Design methods, frameworks and architectural matrices incorporate the risk of becoming a restriction rather than an enabler. The difficulty lies in finding the in-between-state where (informative) data provides enough restrictions so that no longer *everything is possible, thus nothing happens*, but still remains open enough to enable intuitive moments of creativity. When used by architects (or similar), it is encouraged to take in as much information as required to spark that moment of creativity and act on it, leaving the factor list be (for the moment). Once inspiration dies out, return to the factor list, discover new restrictions which in turn enable new potentials to emerge on the periphery. In other words, the architect has an responsibility to act on the provided boundary conditions instead of meaninglessly adding restriction upon restriction.

Project's Design Phase

When exploring the architectural integration of PFALs into the (urban) environment during the Design Phase of this project, the findings as listed in the conclusion are used during the decision-making process. When more in-depth knowledge is required to understand the implications of a design choice, the factors list is consulted.

For example, a recommended starting point is to look at the contemporary supply chain and how the end consumers interact with their food (1.2 & 1.4). Discover for different urban scenarios what vertical farming can contribute to enabling a more elegant, sustainable and socially inclusive environment. For an academic project, there exists a friction in choosing the path of exploring what is theoretically and/or physically possible to build versus what is economically reasonable.

With these recommendations in mind, the Design Phase of this project will research the following building(scale) typologies: *residential, building complex, city block, city*. Depending on the results from these analysis, two leads of integrating vertical farming are explored; 1. Supermarket & residences; 2. Distribution centre & experience centre. The location of these design studies is situated in *De Randstad* (The Netherlands).

Outlook

Plant Factories with Artificial Lighting are proving to be one of the future forms of farming, but to solve the bottleneck of energy consumption and enable a positive impact to the consumer's wellbeing by interacting with the production process, investments in research from an architectural and building engineering perspective are key. All in all, with an interdisciplinary and collaborative effort the future seems green, purple and close to home.

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Figures

Fig. 1. Searchinger, T., Waite, R., Hanson, C., Ranganathan, J., Dumas, P., Matthews, E., & Klirs, C. (2019). *Creating a sustainable food future: A menu of solutions to feed nearly 10 billion people by 2050. Final report*. WRI.

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- The New Farm, The Hague (The Netherlands). – Rooftop vertical farm
- Van Gelder, Ridderkerk (The Netherlands). – Distribution centre.

Appendix

The Factors List

Not included in this publication, please contact S.J.Verdegaal for complete document.

Chapter 1 | ENVIRONMENTAL CONTEXT
- Geographical Climate Conditions
- Economic Climate Conditions
- Cost Estimation
- Site

Chapter 2 | PLANT GROWTH
- Basics of Plant Growth INPUT
- Basics of Plant Growth OUTPUT
- Vertically Farmed Crops
- Hydroponics
- LED
- Automation

Chapter 3 | CONTROLLED ENVIRONMENT SYSTEMS
- HVAC System
- Lighting System
- Water System
- Waste Management System
- Smart Devices

Chapter 4 | ENERGETIC FLUXES
- CEA System
- Building
- Urban Environment
- Renewable Energy Sources

Chapter 5 | SPATIAL FUCTIONS
- Minimal Required Functions
- Additional Functions: Within Supply Chain
- Additional Functions: Outside of Supply Chain

Chapter 6 | BUILDING STRUCTURE
- Load Bearing Structure
- Façade
- Transparency
- Materials