VERTICAL FARM GROWING TRAY

Enhancing the climate uniformity in vertical farms by growing trays with integrated ventilation for improved crop production.

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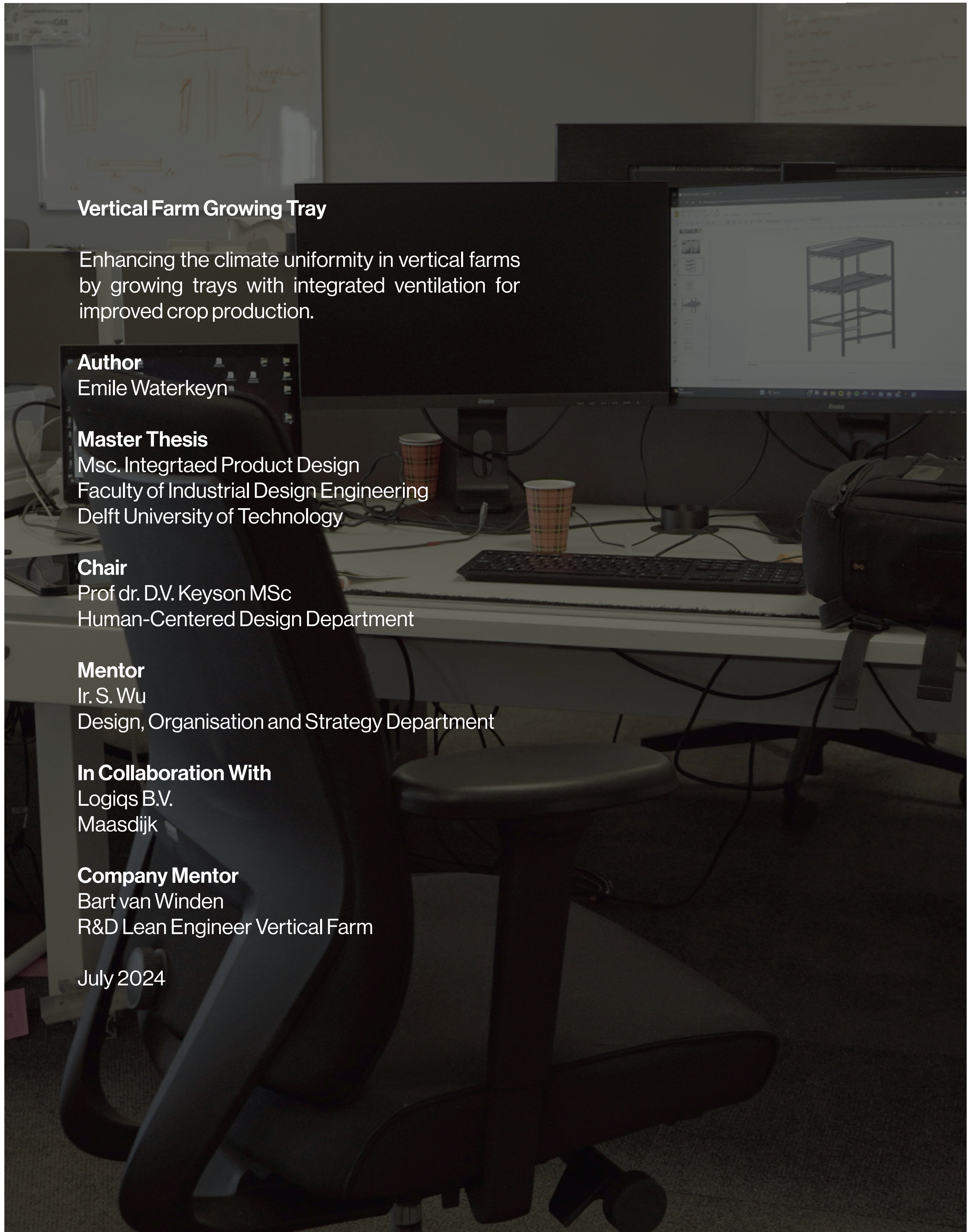

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Preface

I want to take a moment to thank my chair and mentor, David Keyson and Sijia Bakker Wu, for their guidance and support throughout this project. Thank you both for your time and efforts.

I would like to extend my gratitude to my company mentor, Bart van Winden at Logiqs for introducing me to the world of hortitech and arranging various vertical farms visits. Your assistance went beyond the scope of this project, offering me a broader understanding of the industry.

A special thanks to Jeffrey and Thomas at Logiqs, who provided practical advice and assistance. I had a great time being on your side for five moths.

I am grateful to the experts who contributed to this project. Thank you to PhD candidate Luyang Kang for presenting your research on ventilation in farms. Tess Blom and Dr. Andy van de Dobbelsteen, thank you for inviting me to the Skyhigh consortium and facilitating connections within the vertical farm industry. Gert-Jan van Staalduinen, your guidance at Logiqs and efforts in exploring graduation opportunities were valuable. Jan Westra from Priva, thank you for your help in understanding the vertical farming market and guiding me to Logiqs.

Thank you to the team at SIGN (Stichting Innovatie Glastuinbouw Nederland), especially Peter Oei, for your support during my exploration of the horticulture industry in the Netherlands.

It has been a long process with many people involved that went further than only a graduation project. I am lucky I got to meet so many interesting people thinkering with this wicked food problem.

Finally, I would like to thank my friends and family for your support throughout my studies. Merlijn, Freek, Rijk, Barend and Renee, thank you for supporting me and providing encouragement it was a nice to be able to share this little adventure with all of you.

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CHAPTER ZERO

SUMMARY

The summary reviews the key outcomes of the design process and validation. It provides an overview of the main results for you to get a glimpse into the project.

00.

The thesis “Vertical Farm Growing Tray” aims to enhance climate uniformity in vertical farms by integrating ventilation systems into growing trays to improve crop production. This project is part of my Master’s degree in Integrated Product Design at Delft University of Technology, conducted in collaboration with Logiqs B.V., a company specializing in horticulture technology.

The project began by exploring various urban farming models to address global food system challenges. Through site visits and interviews, I identified controlled environment automated farming as a viable solution, optimizing plant growth by precisely controlling environmental factors. To get a perfect climate, uniformity within the climate of the farm needs to be achieved. One way to do this is by integrating vertical ventilation within the farm which I is my goal for this project. I have designed a growing tray (1) and a vertical farm system (2) with integrated vertical ventilation.

The design process of the growing tray involved several phases, starting with literature research to establish design requirements of which seven ideas were developed from. Three ideas were further developed into concepts. I chose one concept for further development. This design utilized a corrugated perforated roof to create channels for air distribution and proper irrigation.

Prototyping and testing were crucial steps in validating the design. I developed a mini farm prototype and used CFD simulations to refine the design, resulting in a balanced airflow system that minimized microclimates within the plant canopy.

The PFAL system developed in this project consists of several integrated components. The structured approach ensured a comprehensive understanding of the system’s performance at various levels, from individual plants to full-scale farm operations. The design allowed for scalable and modular farm setups, making it feasible to operate multiple rows of trays with minimal space requirements.

This project resulted in a PFAL system design that enhances climate uniformity and crop production through innovative integration of ventilation, lighting, and irrigation within the growing trays.

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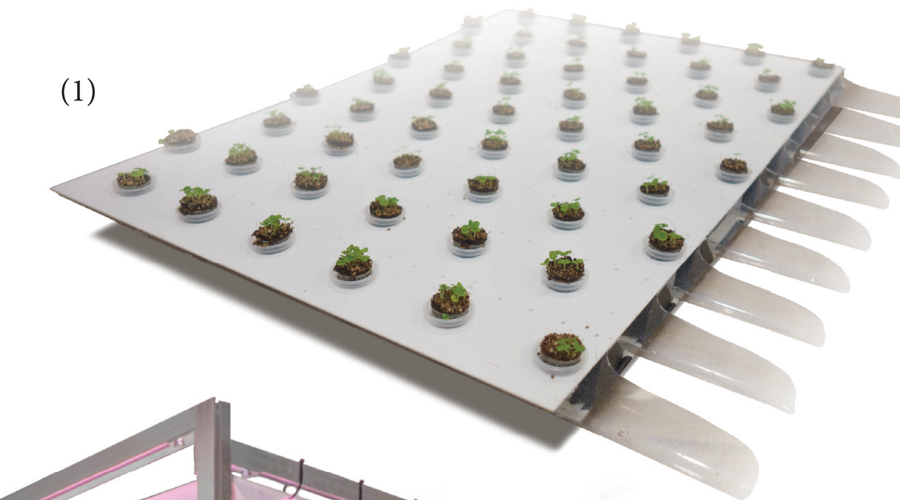


(2)

CHAPTER ONE

INTRODUCTION

The introduction to my project involves explaining how I arrived at this project and outlining my main intentions. This phase began with examining our food system and considering ways to enhance its resilience, particularly through the development and promotion of urban farms.

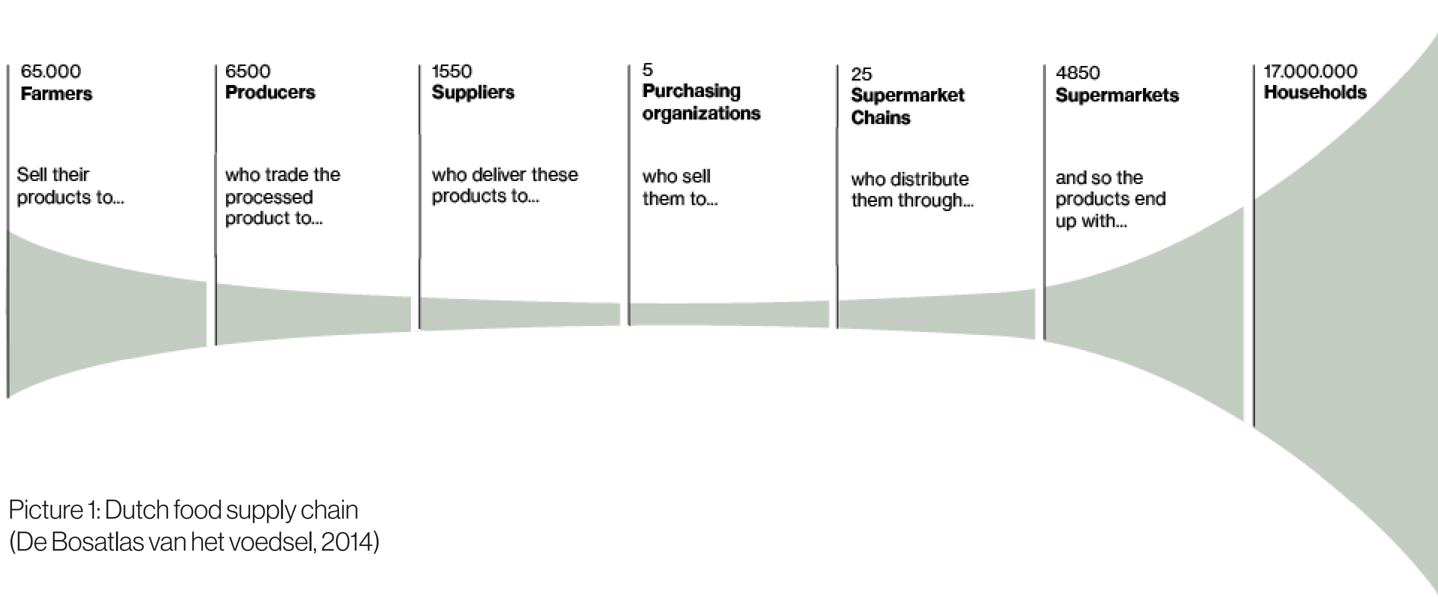
01.

1.1 - Building a Resilient Food System

Climate change, land degradation, population growth, pandemics, biodiversity loss, pesticide use, resource constraints, and rapid urbanization are putting huge pressure on our food supply chain. People are trying to adapt a healthy, locally sourced, plant-based diet with a smaller environmental impact. However, coping with the logistic involving a lot of stakeholders remains very difficult, resulting in 24% of food never reaching consumers (FAO, 2021). With the global population estimated to reach 9.8 billion by mid-century, the problem of feeding more mouths with the same resources becomes even more difficult (United Nations, 2017).

The agriculture industry is responsible for over 70% of global water consumption and 17% of CO2 emissions (FAO, 2020; IPCC, 2019). The land use for food production, includes the loss of 10 million hectares of forest annually, shows the importance for change (FAO, 2020). Currently, 38% of the world's land surface is assigned to agriculture (FAO, 2020). To transform our food system, consumer behavior must shift together with technological advancements, producing local production and smaller, more flexible supply chains.

The Dutch horticulture industry is known for its innovative practices, especially in the Westland region. It faces a weird paradox in its supply chain. Despite its efficiency and high output, a lot of the domestically grown products are being exported, while most of the products found in our supermarkets are imported products. (Baarsma, 2020).This supply chain involves a lot of stakeholders, with a few key players having a big influence, as shown in Picture 1. These important key 'middle' stakeholders shape pricing, distribution, and market dynamics, showing the need for a more resilient food system. Which requires a shift in scale, in consumer behaviour, and in producing methods and technologies.



Picture 1: Dutch food supply chain (De Bosatlas van het voedsel, 2014)

Picture 2: Victory Garden (CBS News)

Victory Gardens, also known as War Gardens, enhanced food security in the U.S. during World Wars I and II by encouraging citizens to grow their own food. This reduced reliance on national supply chains, alleviated transportation strains, and ensured a steady supply of fresh produce, making the food system more resilient during crises.

1.2- Urban Farming Models

Urban farming models shows how a shift towards self-sufficiency and closed-loop farming could take place. Pushing communities to reduce their reliance on existing food supply chains while growing produce closer to their consumers. Through five site visits and interviews with urban farmers, I gained insights into a variety of models and mindsets driving individuals to produce their own crops.

Rooftop Farm
I visited a rooftop farm focused on community involvement and education. Crops are grown in soil, and the farm is very community driven, putting more focus on education and less on yield poroduction.

Rooftop Greenhouse
A rooftop greenhouse showed high production levels and efficiency, utilizing hydroponic and aquaponic systems for maximum yield and local sales.

***Container Farm**
An automated container farm showed a commercially viable subscription model, highlighting efficiency and scalability in urban agriculture.

Farm-to-Table Restaurant
A farm-to-table restaurant sourced crops directly from an farm, putting their focus on local food sourcing and sustainable food practices.

Indoor Vertical Farm in Attic
An indoor vertical farm in my attic space for personal production showed an attempt at a more self-sufficient system.

*I decided to continue my research on controlled environment automated farming, as it is a viable technology to transform the food system. This approach optimizes plant growth through precise control of environmental factors and automates tasks like planting, watering, and harvesting. It increases productivity, reduces labor costs, and maximizes crop yield.

Picture 3: Urban Famring Models

CHAPTER TWO

EXPLORATION

The exploration phase is divided into five sub-questions, each building upon the previous one. In this chapter, I delve into the literature research necessary to establish my design requirements and wishes. Each section concludes with a brief summary of the most important information.

02.

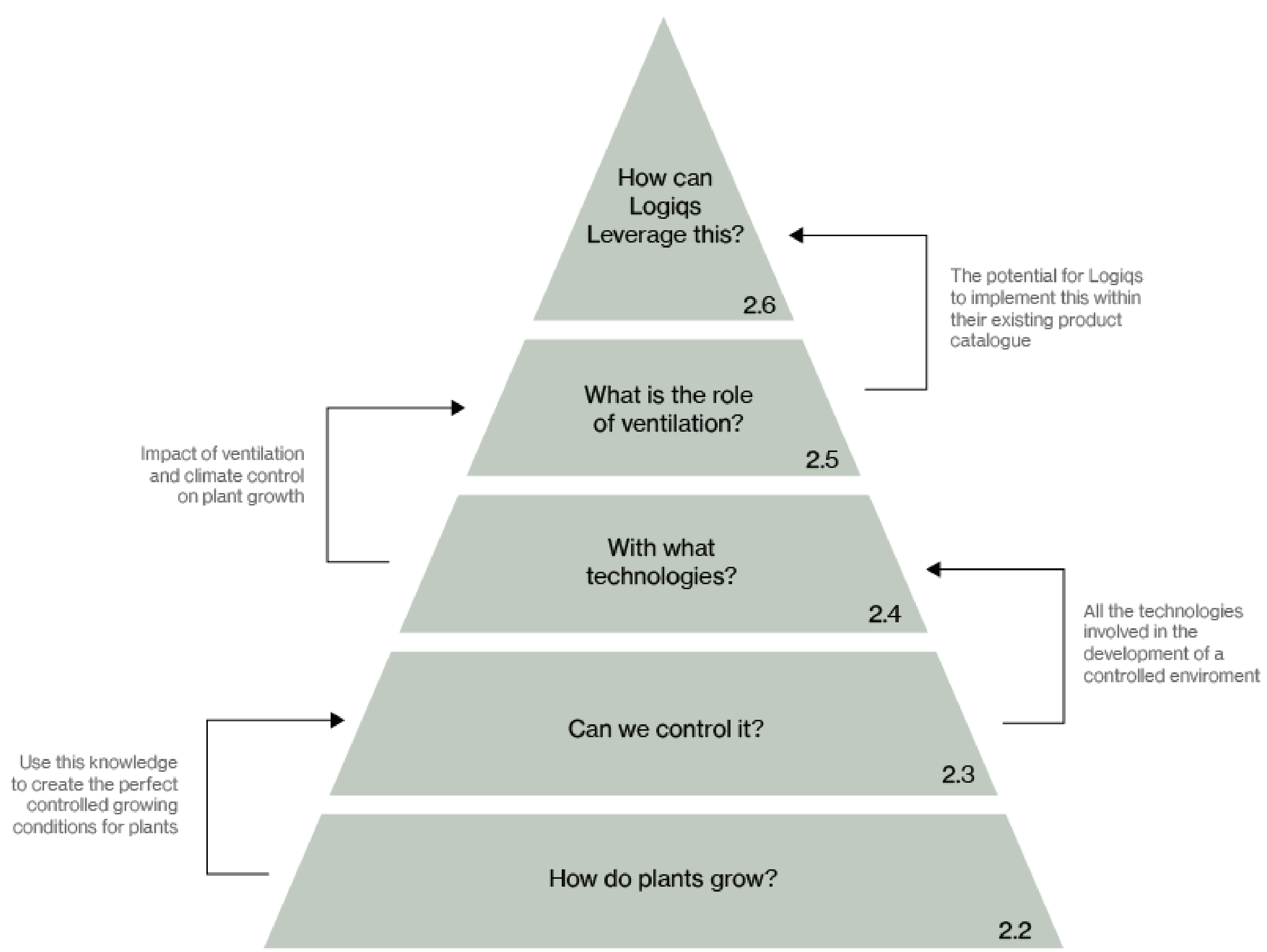
2.1- Introduction

This chapter dives into the essentials of designing Plant Factories with Artificial Lighting (PFALs). It begins by exploring how plants grow, focusing on their physiological processes and key components crucial for their development.

Next, we examine PFALs, where these natural growth processes are recreated artificially to enhance crop yields. By studying how hop plants grow, we learn how to improve production in controlled environments.

Following this, we delve into the technologies behind PFALs, delving deeper into ventilation and climate control, which are vital for optimal growth.

Lastly, we introduce Logiqs and explore its potential to integrate these technologies into existing infrastructures.



Picture 4: Research Approach Visualisation

2.2- Plant Growth Fundamentals

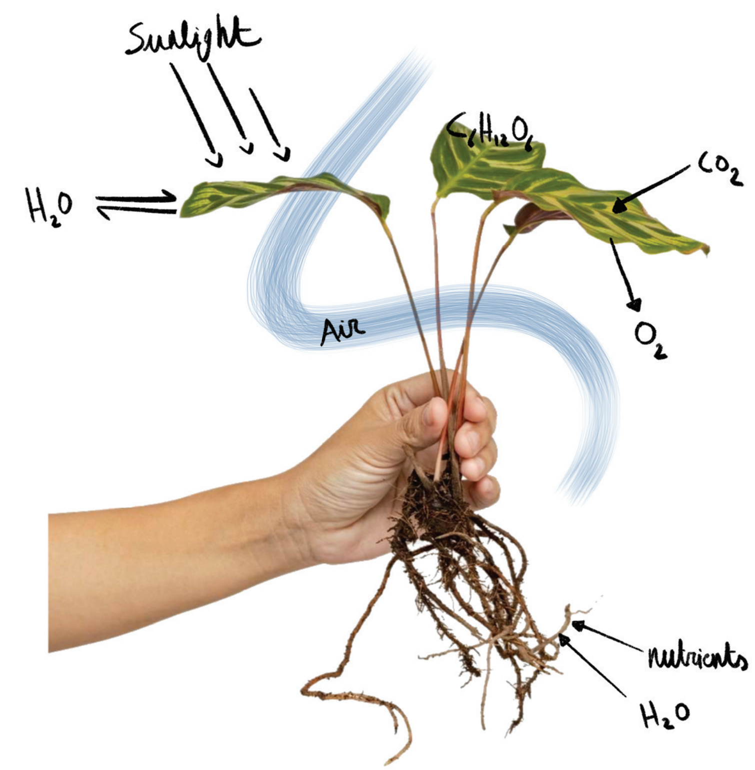
To be able to fully understand and optimize PFAL's, it is Crucial to get a grasp of the essential requirements of plant growth. During the vegetative growth phase of the plant, tree main processes take place on the leaf surface; Photosynthesis, Respiration, and Transpiration.

Photosynthesis* is the process by which green plants use sunlight to get nutrients (glucose) from carbon dioxide (CO_2) and water (H_2O). Chlorophyll in the chloroplasts captures light energy, which is used to convert CO_2 and H_2O into glucose and oxygen (O_2).

Respiration** is the process of changing glucose produced during photosynthesis into usable energy (ATP) for the plant's cellular activities. It takes place in the mitochondria and involves the breakdown of glucose with oxygen to produce carbon dioxide, water, and energy.

* $H_2O + CO_2 + \text{light} \rightarrow O_2 + C_6H_{12}O_6$
water, carbon dioxide, sun → oxygen, glucose (sugar)

** $O_2 + C_6H_{12}O_6 \rightarrow H_2O + CO_2 + ATP$
oxygen, glucose (sugar) → water, carbon dioxide, energy



Finally, transpiration takes place the the plant's surface during which water vapor from the aerial parts of the plant is being evaporated, mainly through stomata in the leaves. Transpiration helps in nutrient uptake by Increasing the upward movement of water in the plant, cooling the plant similar to how sweating cools the human body, and maintaining turgor pressure which is key for mainting structural integrity and driving cell Expansion.

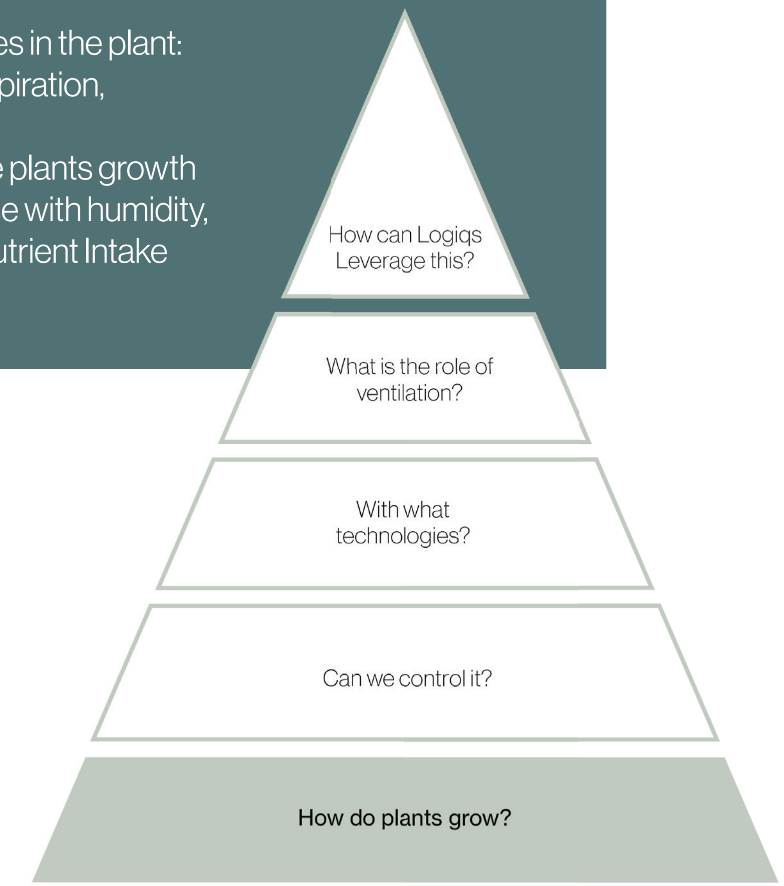
An important very tiny part of the plant is responsible for most of the plant's growth processes. It is the plant's stomata (Picture 5), mainly located on the underside of the leaves.. They could be seen as the mouth of the plant that allows it to breath. They allow the plant for gas exchange, taking CO_2 in and releasing O_2 after Photosynthesis. Additionaly, the transpiration happens trough the stomata.

Each stoma is Equipped with a pair of guard cells that controls its opening and closing, wich are regulated by Environmental factors. Only when the stomata is open, can the plant's physiological process happen and is the plant able to grow. It is therefore important to understand these for optiomal plant growth. The stomata generally opens only with the presence of light. High CO_2 concentrations can cause the stomata to close. In conditions of water stress, the stomata closes as well to prevent exessive water loss. High relative air humidty increases the chance of mold forming, which cuases the stomata to close. (Fanourakis et al., 2020) For optimal growth, the CO_2, temperature, relative air humidiy, water and nutrient intake needs to be regulated accordingly.

Picture 5: Visualisation of the plant's stomata open (left) and closed (right) (Vajiram and Ravi, 2024)

2.2.1- Benefits of PFAL

- Three main processes in the plant: Photosynthesis, Respiration, Transpiration
- Stomata controls the plants growth
- Stomata Open/Close with humidity, CO2, Light, Water, Nutrient Intake



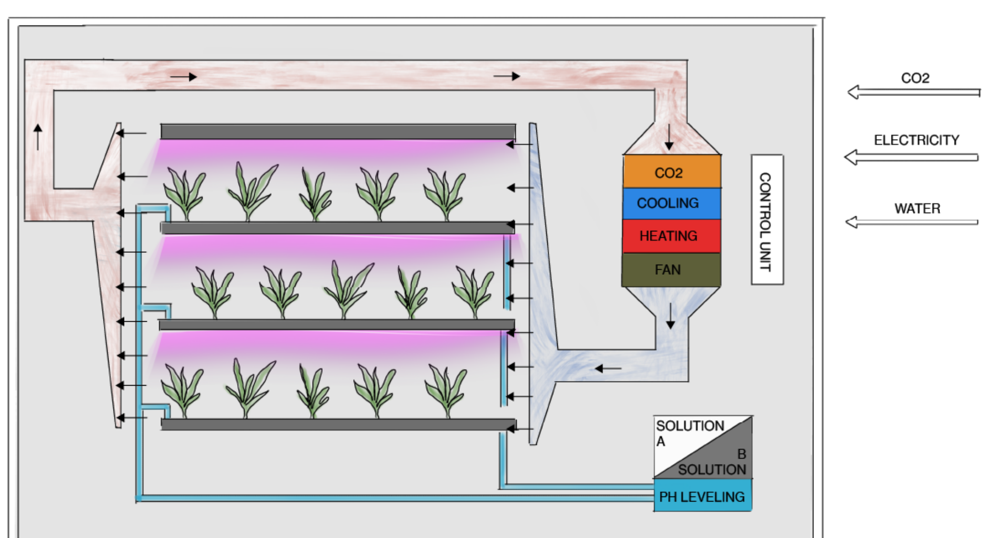
2.3- Plant Factory with Artificial Lightning

In recent years, plant factories with artificial lighting (PFALs) or vertical indoor farms have emerged as an important innovation in agriculture. These highly controlled, indoor environments leverage advanced lighting technologies and precise environmental controls to optimize plant growth and productivity. By providing artificial light, regulating temperature and humidity, and delivering nutrient solutions, PFALs create ideal conditions for cultivating a wide range of crops year-round, regardless of external weather conditions. This chapter goes into how the principles of plant growth are applied and enhanced in plant factories, exploring its potential to transform the food insutry.

The plant's complex requirements need a perfect climate, which is difficult to achieve in the open air. Traditionally, plant development depends on external factors and seasonal changes, making it challenging to ensure a consistent supply of fresh produce throughout the year. Extreme and changing weather patterns further complicate this process, which makes PFALs more appealing for the industry.

2.3.1- Key components of PFAL

To understand PFALs, it is essential to grasp their key components. First, plants are grown soilless using hydroponic techniques. The plants are stacked in vertical farming structures to maximize space efficiency. This setup necessitates the use of advanced lighting systems to ensure proper plant growth. A climate control system is crucial for maintaining the ideal environment, monitored and adjusted by sensors. Automation and IoT integration streamline operations, providing precise control and optimization of the growing conditions.



Picture 6: Vertical Farm Components

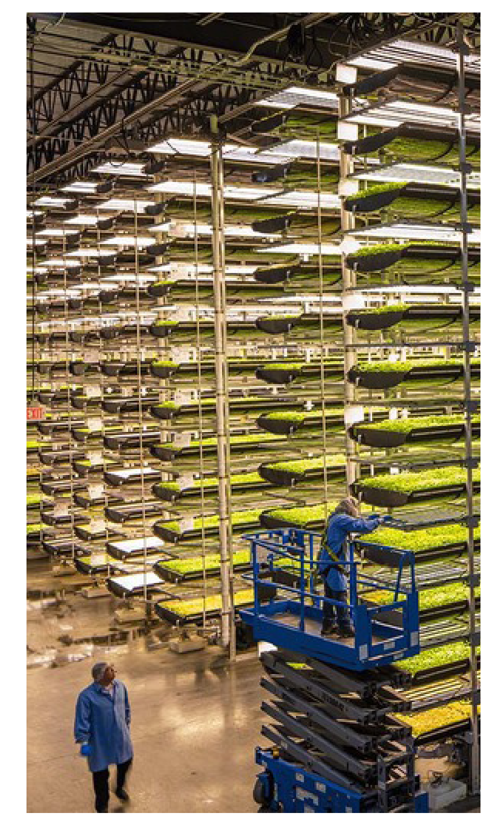
Hydroponic Systems
Most PFALs employ hydroponics, a soil-less growing technique where plants receive nutrients through water-based solutions. Hydroponics conserves water, reduces the risk of soil-borne diseases, and allows for precise nutrient management.

Vertical Farming
Stacking multiple layers of crops in vertical racks increases yield per square foot, making it possible to produce large quantities of food in a relatively small footprint.

Lighting Systems
These lights can be tuned to emit specific wavelengths to optimize plant growth at different stages, from germination to flowering. LEDs are energy-efficient, produce less heat, and have a longer lifespan compared to traditional lighting, making them ideal for PFALs.

Climate Control
HVAC (Heating, Ventilation, and Air Conditioning) systems are used to maintain the best temperature,, humidity, and CO2 levels.

Automation and IoT
Sensors and control systems monitor and adjust environmental parameters in real-time. Automated systems handle tasks such as watering, nutrient delivery, and light adjustments, reducing labor costs.



Picture 7: Inside Aerofarm's Vertical Farm, 2021

Picture 8: Inside Bowery's Vertical Farm, 2019

2.3.2- Benefits of PFAL

In today's world, climate change, environmental damage, and limited resources make traditional farming difficult. PFALs is a new solution that can change this. The following are the main benefits PFALs brings to the industry.

Year-round crop production
This enables continuous cultivation of crops throughout the year, unaffected by seasonal variations or extreme weather conditions. Which is particularly appealing for lands with a unstable climate, and lands with less (or no) sunlight during the day in some parts of the year.

Consistent crop yield
Provides reliable and predictable yields, ensuring a steady supply of produce regardless of external climate factors.

No agricultural runoff
Prevents water pollution by eliminating harmful runoff into rivers and lakes, preserving local water quality.

Ecosystem restoration
Frees up land previously used for traditional farming, allowing for the restoration of natural ecosystems and increased biodiversity

No chemicals
Avoids the use of pesticides, herbicides, and synthetic fertilizers, leading to healthier produce and a safer environment.

Resource efficiency
Uses 70-95% less water and significantly fewer fertilizers compared to conventional farming methods, conserving essential resources. Which is especially appealing for lands with water scarcity.

Reduced food miles
Locates food production closer to urban centers, significantly cutting transportation distances and reducing carbon emissions. Which is specifically appealing for alnds in a dense urban area able to provide food for many consumers living neaby

Food safety and security
Enhances control over growing conditions, improving food safety and reducing the risk of contamination and foodborne illnesses.

2.3.3- Challenges of PFAL

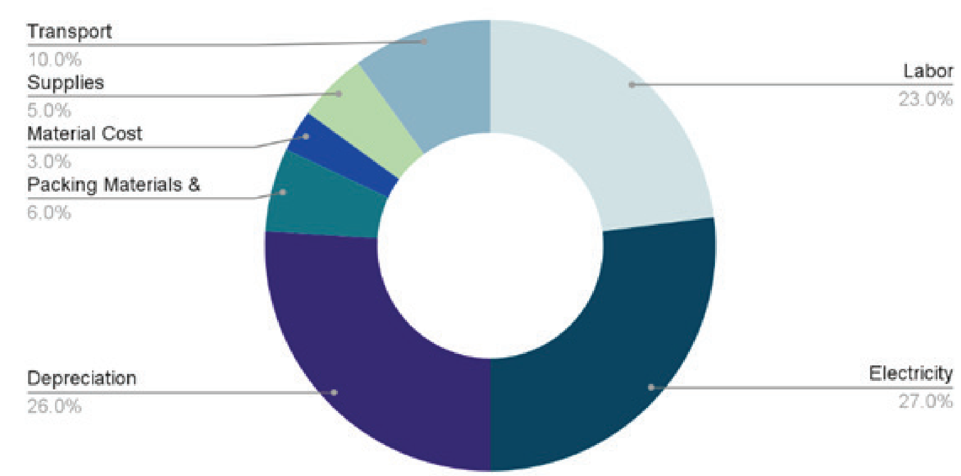
While PFALs offers many benefits, it also comes with several challenges that need to be addressed for successful implementation.

Energy Consumption
Despite the efficiency of LED lighting, PFALs still require substantial energy for lighting and climate control. Natural resources could be used as an energy source, being able to tune the grid with the farm for plants to grow when there is an energy overload on the grid.

Technical Expertise
Being able to run a farm as such requires specialized knowledge in horticulture, engineering, and data management. Current farmers does not have the skills to run a PFAL.

High Initial Investment
The setup cost for PFALs is significantly higher than traditional farming due to the need for advanced technology and infrastructure.

Economic Viability
The economic viability depends on factors such as crop selection, market demand, and local energy costs. High-value crops like leafy greens, herbs, and microgreens are often more economically feasible. The following chart depicts the running costs of a vertical farm. The biggest cost is the electicity use mainly due to high energy consumtion of the led lighting.

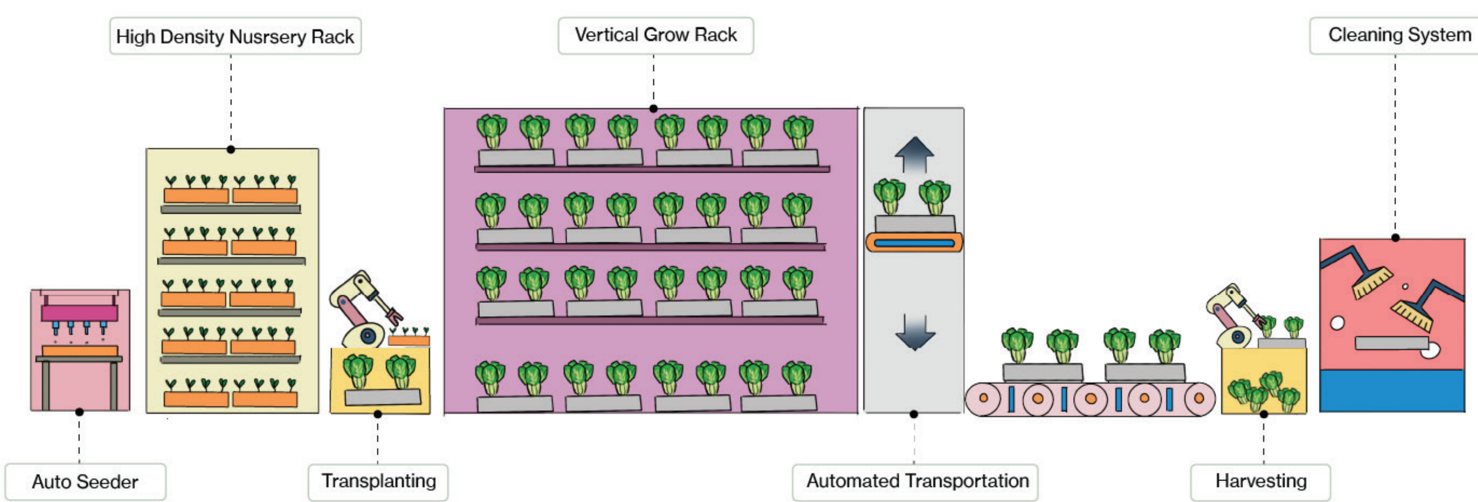


Graph 1: Running costs of vertical farming breakdown.
Spead Co. Ltd. Kyoto Japan
(Plant Factories, 2019)

2.3.4- Growing Process of PFAL

Picture 9 is a depiction of the growing process in a PFAL. It shows the different steps undertaken for crops to grow.

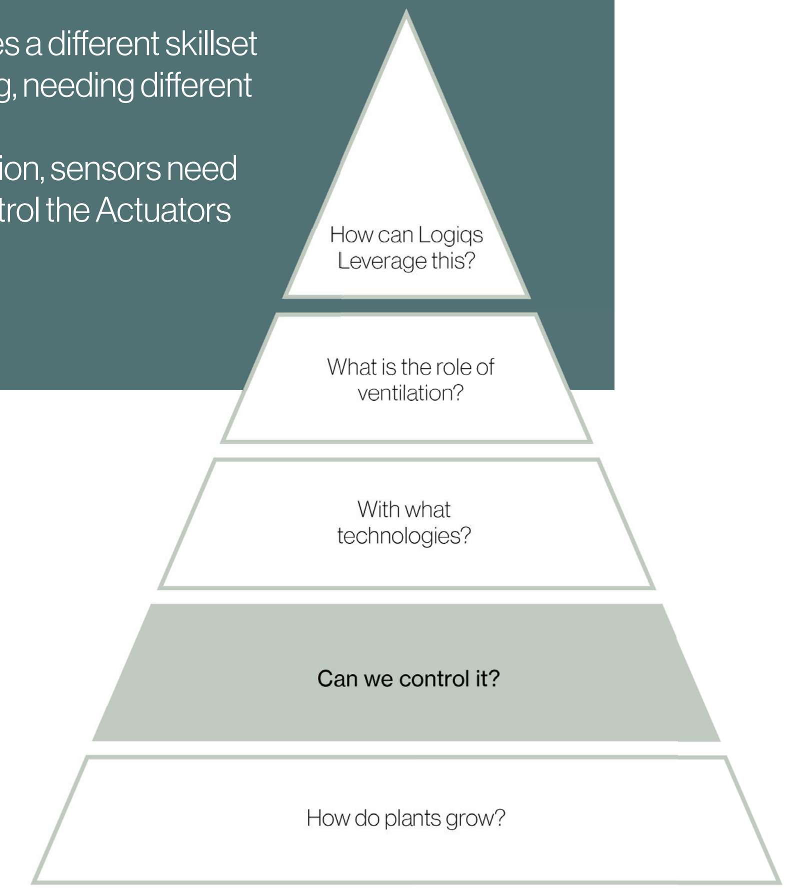
First, the auto seeder dispenses the exact amount of seeds into the substrate. Next, the substrate is brought to the nursery rack where the plants germinate and root production is stimulated. Then, the plants are transplanted into vertical growing racks where they complete their growth cycle. Once mature, they are transported to the harvesting facility where the crops are packaged. Finally, the growing racks are cleaned and prepared for the next cycle.



Picture 9: Vertical Farm growing process

2.3.5- Conclusion

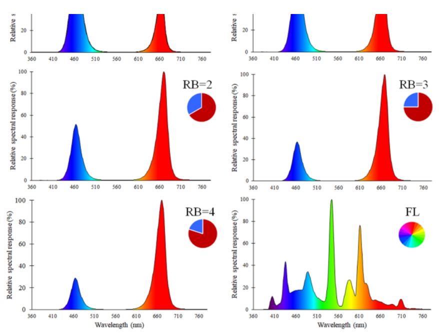
- Plant Factories are to big of an investment to be viable at this point in time.
- Plants need to be transplated during their growing process since they take up more space.
- Runing a VF requires a different skillset then regular farming, needing different expertises.
- For a PFAL to function, sensors need to be placed to control the Actuators correctly.



2.4- Integrated Technologies in PFALs

PFALs depends on the adaptations of some technologies to create optimal growing conditions for plants. This chapter explores the key components and technologies essential for PFALs, including lighting systems, irrigation, growing mediums, climate control, sensors, and ventilation solutions.

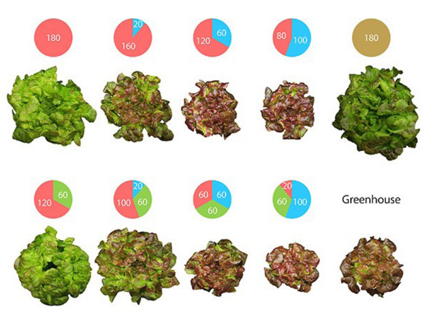
2.4.1 - Lighting



Picture 10: Light spectra used in experimentation on lettuce growth. Finding the moest resource efficient light spectrum for crop cultivation (Pennisi et al., 2019)

Lighting is a crucial factor in Plant Factories with Artificial Lighting (PFALs), as it directly influences plant growth and development. Unlike traditional farming, where the sun provides natural light, PFALs rely entirely on artificial LED lighting systems. These systems must be carefully designed to provide the appropriate light intensity, photoperiod (duration of light exposure), and spectral quality.

The spectrum of light provided by artificial lamps differs from natural sunlight, which includes ultraviolet (UV), visible, and infrared radiation. In PFALs, light spectra can be customized using different combinations of LEDs to provide specific wavelengths that optimize photosynthesis and photomorphogenesis. Red light is most efficient for photosynthesis, but a combination of blue, green, and red light is necessary for healthy plant development. Far-red light can influence plant morphology, such as stem elongation and flowering. (Carpineti et al., 2024)



Picture 11: Different lettuce growth with various light recipe's (Meng et al., 2020)

Lighting is the most energy-consuming and expensive component in the initial investment of a PFAL, but the rise of efficient LED lighting has made it crucial to design systems that maximize LED efficiency. Utilizing high-reflection surfaces within the farm can further optimize light usage, ensuring plants receive the maximum possible illumination from the available light sources.

2.4.2 - Irrigation

In PFALs, soilless cultivation methods are typically employed to provide greater control over the growing environment. There are several irrigation techniques used in PFALs, each with its own advantages and applications. In this chapter, we will discuss three common irrigation methods: Ebb and Flow, Deep Water Culture (DWC), and Nutrient Film Technique (NFT).

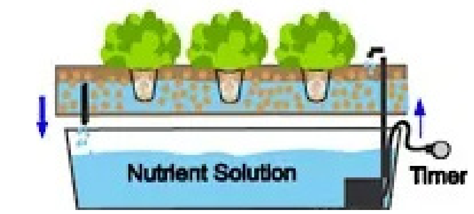
The Electrical Conductivity (EC) of the water, measures the nutrient level in the water and the PH level of the water is closely managed and adapted to the plant's recipe. Meanwhile, the plant's need a medium for the roots to develop in. This is often done in Rock-wool or the more sustainable alternative, coconut fibers.

Ebb and Flow

Ebb and Flow, also known as Flood and Drain, is an irrigation method where the growing trays are periodically flooded with water and then allowed to drain.

+ Nutrient Saturation: Ensures roots are thoroughly saturated with nutrients during the flood phase.
+ Aeration: Draining phase allows roots to aerate, preventing root rot and promoting healthy growth.

- Complexity: Requires a reliable timer and pump system to manage flooding and draining cycles.
- Risk of Failure: Pump or timer failure can lead to dry roots or over-saturation, both harmful to plants.
- Maintenance: Requires regular cleaning and maintenance to prevent clogging and algae growth



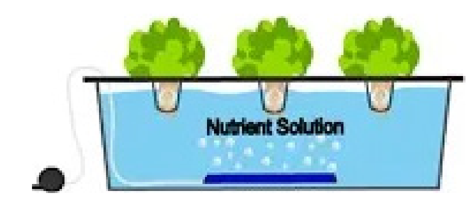
Picture 12: Ebb and Flow Irrigation (NoSoilSolutions, 2023)

Deep Water Culture (DWC)

In Deep Water Culture, plant roots are suspended in a water solution.

+ Rapid Growth: Constant access to nutrients and oxygen promotes fast plant growth and high yields.
+ Simplicity: Easy to set up and manage with fewer moving parts compared to other systems.
+ Consistency: Provides stable conditions for plant roots, minimizing stress and fluctuations.

- Oxygenation: Requires continuous aeration to prevent root suffocation, increasing energy use.
- Temperature Control: Water temperature must be carefully monitored to prevent overheating or chilling of roots.



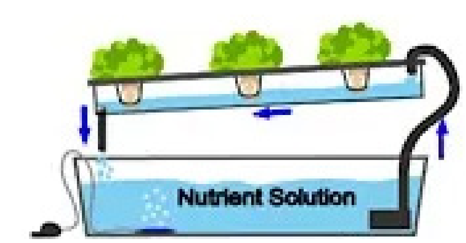
Picture 13: Deep Water Culture Irrigation (NoSoilSolutions, 2023)

Nutrient Film Technique (NFT)

Nutrient Film Technique involves a thin film of water flowing over the roots of plants in a slightly inclined channel. For the best yield, a incline of 3 degrees is advised with a flow of 30L/hour. (Al-Tawaha et al., 2018)

+ Efficiency: Highly efficient in water and nutrient use, reducing waste.
+ Oxygen Access: Exposes roots to both air and nutrients, promoting healthy root development.

- System Sensitivity: Requires precise control of flow rates and angles to ensure even nutrient distribution.
- Maintenance: Channels can become clogged, requiring regular cleaning and monitoring.



Picture 14: Nutrient Film Technique Irrigation (NoSoilSolutions, 2023)

2.4.3 - Climate Control

Maintaining an optimal temperature range is crucial for promoting plant growth and development in PFAL systems. Studies have shown that an optimum temperature range between 20°C and 25°C enhances plant growth and development (Shimizu, 2007).

Relative humidty, in relation with temperature, determines the vapor pressure deficit (VPD), affecting leaf transpiration rates and nutrient uptake. Proper air movement within the PFAL facility prevents stagnant air, ensuring uniform environmental conditions. Studies have demonstrated that maintaining a VPD range between 0.5 kPa and 1.2 kPa promotes optimal plant growth and transpiration rates (Kitaya et al., 2000; Yokoi et al., 2008).

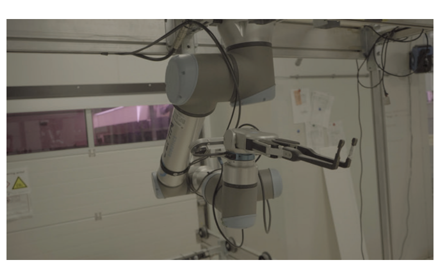
CO2 supplementation is essential for photosynthesis and plant growth in PFAL systems. While the CO2 concentration of the outside air is around 400 ppm, studies have shown that CO2 supplementation at concentrations between 800 ppm and 1200 ppm can significantly enhance plant growth and yield (Kozai, 2013). Supplementation with CO2 tanks or cylinders ensures plants receive optimal CO2 levels for growth and productivity. Precise CO2 management is crucial for maximizing crop yields and quality.

2.4.4 - Sensors and Automation

Picture 15: Camera and sensor in vertical farm at Logiqs

In indoor cultivation systems, leveraging data for optimizing plant growth is gaining traction. Concepts like "data-driven horticulture" and "Artificial Intelligence (AI)" are becoming popular as growers seek efficiency. However, effective AI relies on relevant data representing growing conditions (van Delden et al., 2021).

VF companies collect climate data like temperature and humidity but less frequently monitor plants. Some use cameras for plant monitoring, but integration into automated systems is limited (van Delden et al., 2021).



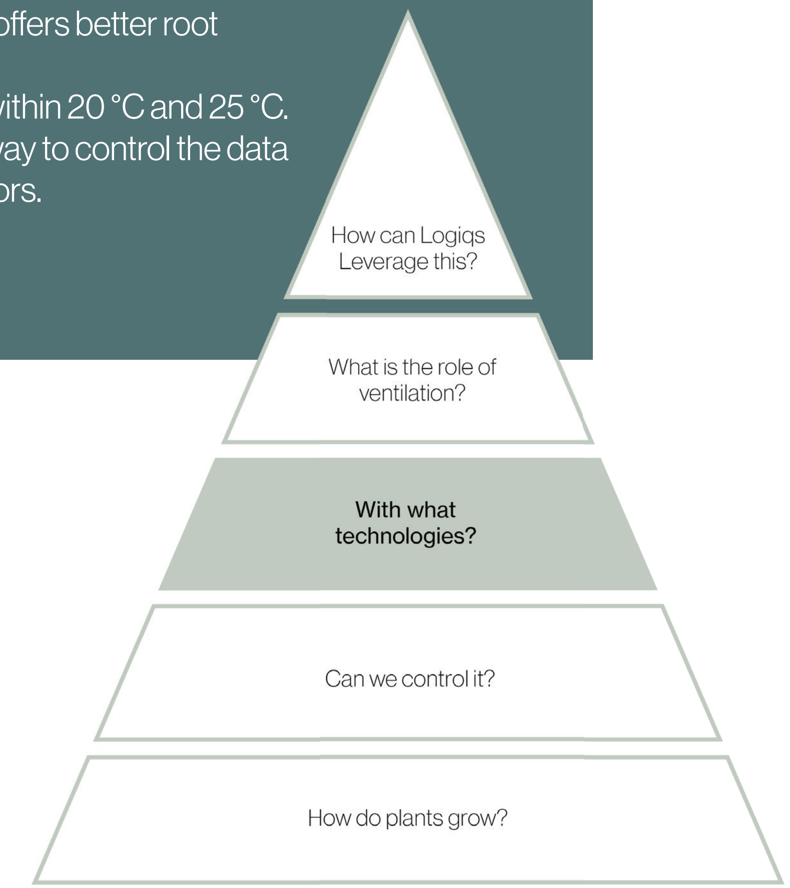
Picture 16: Robot capable of transplanting the plants from a Vertical Farm Tray at Logiqs

By analyzing trends and patterns in the data, growers can identify areas for improvement, optimize resource usage, and enhance overall productivity. For example, data analytics can help identify correlations between environmental factors and plant growth, leading to more efficient cultivation practices.

In addition to optimizing plant growth, sensors and data are also instrumental in automation efforts within VF systems. Automated processes, such as seeding, transplanting, and harvesting, rely on real-time data to ensure accuracy and efficiency. By integrating sensors with robotic systems, VF operators can achieve higher levels of automation, reducing labor costs and increasing overall productivity.

2.4.5- Conclusion

- The inside of a farm is mostly white and reflective for more efficient lightning sulutions.
- While Ebb/Flow irrigation is the industry standard withtin the horticulture, NFT on a 3 degrees angle offers better root development.
- Climate needs to be within 20 °C and 25 °C.
- There needs to be a way to control the data collected by the sensors.

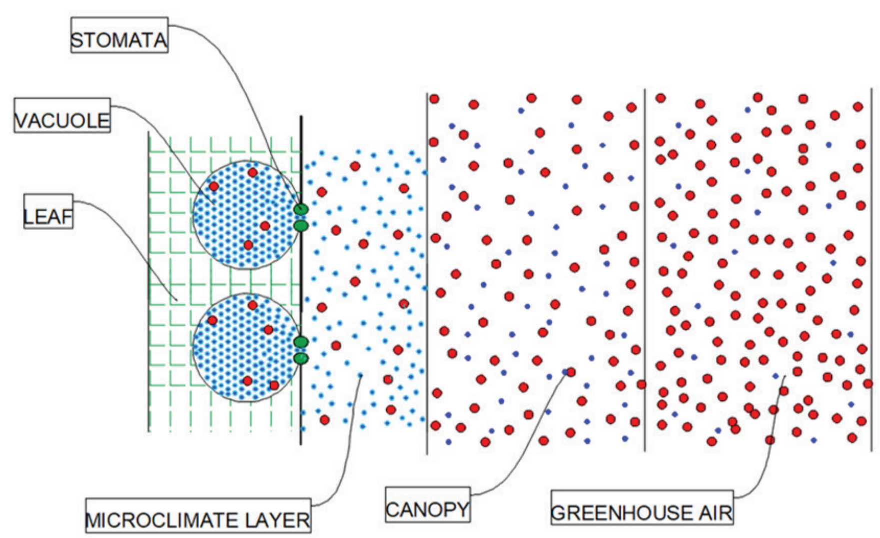


2.5- Ventilation in PFALs

The indoor environment of PFALs is influenced by several factors, including the heat generated by artificial lighting, the multilevel arrangement of crop shelves, and the design of air conditioning and distribution systems. Improper design can lead to environmental nonuniformity. This nonuniformity can manifest as uneven temperature distribution, inconsistent CO_2 levels, and variations in humidity, all of which can stress plants and reduce overall productivity (Gaastra, 1959). To counter this nonuniformity, a proper airflow needs to be introduced in the farm.

2.5.1 - Boundary Layer

The air surrounding a leaf can be divided into three layers. Closest to the leaf is the 'Microclimate Layer', often called the boundary layer. Characterized by stagnant air with no movement. Due to the lack of air movement, this layer tends to have a higher concentration of humidity compared to the general greenhouse air. The CO_2 concentration in the microclimate layer is typically lower than in the greenhouse atmosphere since the plant has consumed most of it already. The high Humidity concentration in the stagnant microclimate layer starts acting as an insulaion layer, hindering the energy exchange of the LEDs to the plants leaf surface. (Yorick, 2020)



Picture 17: Plants Climate Layers (Zhang & Kacira, 2018b)

A dense canopy including very tight spacing of plants impedes air movement and increases boundary layer thickness. Therefore, wind movement needs to thinnen the boudary layer. (Runkle, 2016)

2.5.2 - Effects of airspeed on plants growth

Research by Kitaya (2005) explored how varying air current speeds affect cucumber seedlings. When the air current speed increased from 0.02 to 1.3 m/s for a seedling canopy, The yield increased by 2.8 times. Another study by Kitaya (2000) showed that for individual lettuce leaves, an increase in air current speed from 0.005 to 0.8 m/s led to a 1.7-fold increase in yield. This demonstrates that faster air currents enhance both photosynthesis and transpiration by decreasing the resistance of the leaf boundary layer and removing humid air near the leaf surface, thus increasing the water potential gradient between the stomata and the surrounding air. In this study, Kitaya et al. (2005) emphasize the significance of maintaining an air speed around 0.2 m/s to promote efficient gas exchange and reduce the boundary layer resistance around plant leaves.

2.5.3 - Tipburn

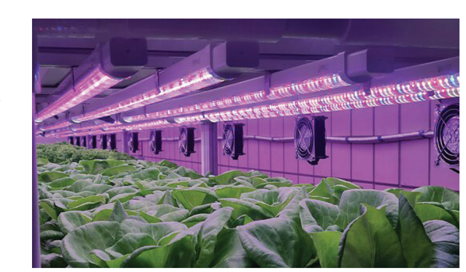
Tipburn, characterized by browning leaf margins, is a symptom of calcium deficiency. Calcium is crucial for strengthening plant cell walls and is passively transported from the roots to the leaves through the transpiration process. In stagnant air conditions, even with high transpiration demand and sufficient calcium at the roots, inner and newly developing leaves with low transpiration rates can develop tipburn. This defect compromises the appearance and market value of lettuce. (Ahmed et al., 2020)

Picture 18: Tipburn on a lettuce plant (Urban Ag News)

Lee et al. (2013) examined the occurrence of tipburn in two sensitive cultivars under four different horizontal airflow rates in an indoor plant factory. Using three air-circulating fans placed horizontally along the sides of the beds, they found that a stable horizontal airflow of about 0.3 m/s significantly reduced tipburn incidence. Despite this, tipburn was still detected in the inner leaves near harvest, with a reduction of 65% and 55% in tipburn for the two cultivars at an air current speed of 0.28 m/s compared to the control group without airflow.

2.5.4 - Latheral Air Supply

Most PFAL's ventilation is desiged for a latheral airflow. On one side of the plan's conopy, air in being blown, and on the other side the air is being exhuasted. This creates a airflow that is blown above the plant's canopy (Zhang & Kacira, 2018b).



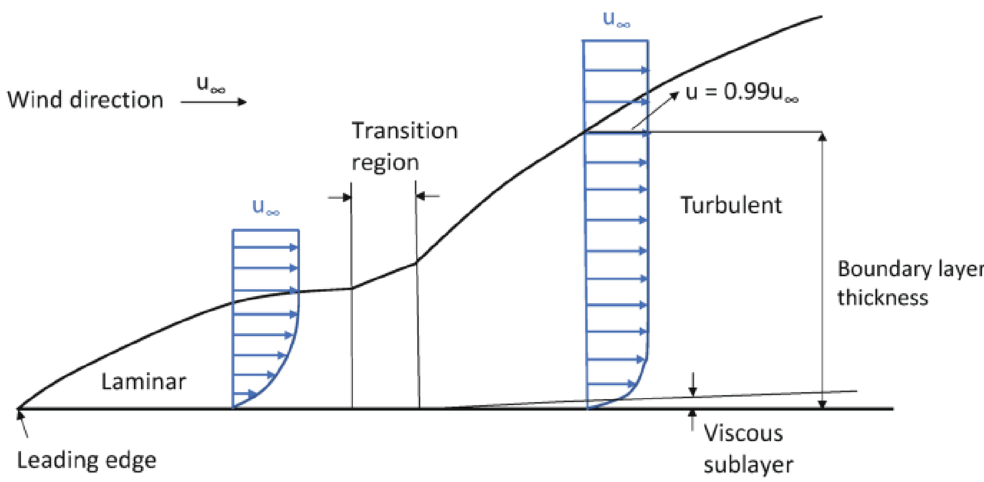
Picture 19: Farm with Latheral air supply (vrt, 2022)

This makes sense since it is a cost effective way of achieving air movement in the whole farm. However, there are a few issues encountered by this method:

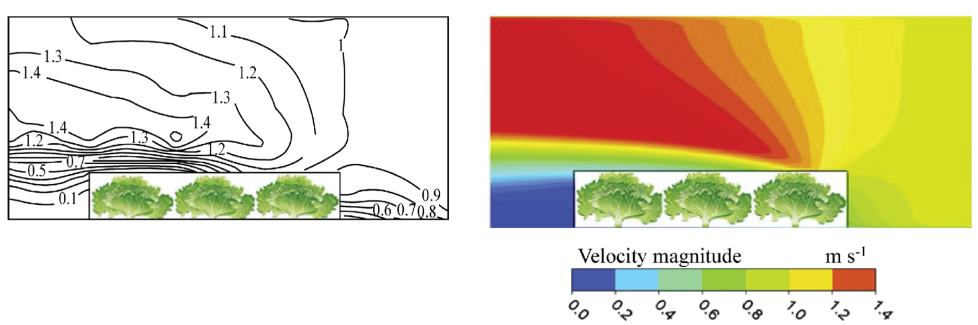
1. Boundary Layer resistance

The leaf boundary layer creates resistance, generating friction against the laterally incoming air. This resistance, known as boundary layer resistance (BLR), impacts the efficiency of airflow around the plant (Nobel, 2009).

As the air moves past the plant, the leaves induce turbulence, causing the boundary layer to grow thicker. A thicker boundary layer results in a decreased relative speed of the air, meaning there is a significant difference in airflow speed between the beginning and the end of the leaf. This can reduce the effectiveness of air movement, leading to less efficient gas exchange and potentially impacting plant growth and health. (Zhang & Kacira, 2018c)



Picture 20: Depiction of the Boundary Layer Resistance over the crop's canopy (Zhang & Kacira, 2018c)



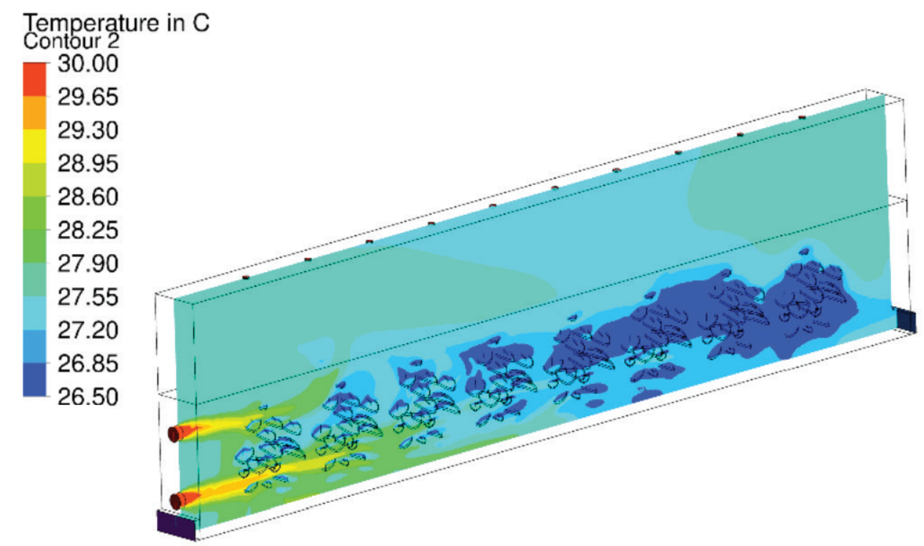
Picture 21: Air velocity based on experimental data in wind tunnel and simulated Boundary Layer Resistance (Fang et al., 2020)

2. Microclimates builtup

In PFALs vertical farms with lateral airflow, several issues arise due to the development of microclimates within the dense plant canopy. When air is blown laterally, it often fails to penetrate effectively between plants, leading to stagnant air pockets. This stagnation traps humidity and prevents the proper exchange of CO_2.

The inconsistency in air movement creates varied environmental conditions within the canopy adn microclimates within the canopy. Lower leaves and plants experience different temperature, humidity, and CO_2 levels compared to upper leaves, resulting in uneven growth.

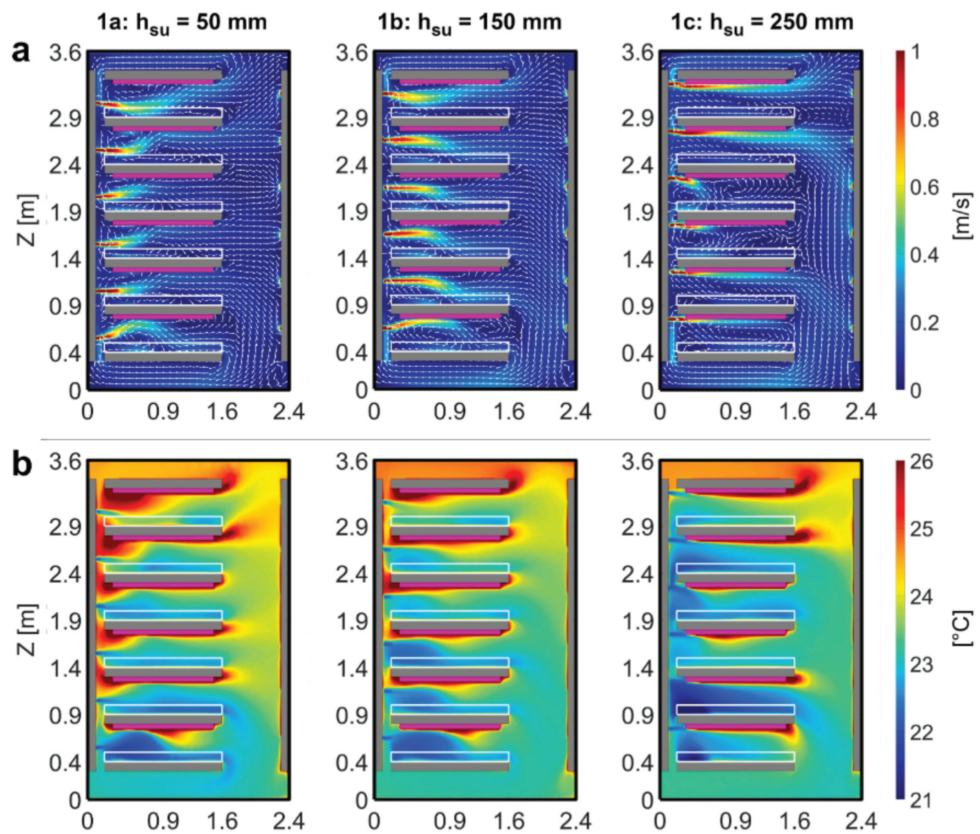
Moreover, the stagnant microclimates foster ideal conditions for pests and pathogens to thrive. The lack of proper air circulation allows pests to accumulate and proliferate within the plant canopy, increasing plant stress and the potential for crop losses.



Picture 22: CFD Model of a row of plants with air being blown on one side. The air is passing above the plant's canopy, but stuggles to get inbetween the plant to regulate temperature. Study conducted by the Univerty of Gent (Plas & Michel, 2022)

3. Convection

In vertical farms with lateral airflow, convection creates significant challenges due to the uneven distribution of temperature, humidity, and CO2 across different layers of plants. The LEDs significantly heat the air around them, and when this warm air is blown laterally, it mixes with the cooler air on the plant surfaces. Eventually, this mixed air rises to the layers above, resulting in thermal difference with warmer air at the top and cooler air at the bottom.



Picture 23: Impact of vertical distance of air supply on the air distributions in the vertical central cross section: (a) air velocity, (b) air temperature. (Kang & Van Hooff, 2024)

2.5.5 - Vertical Air Supply

To address the problems of boundary layer resistance, microclimates within the canopy, and convection in vertical farms, vertical airflow presents a promising solution. By delivering air from beneath the plants, vertical airflow effectively disrupts microclimates, allowing humidity and CO2 to reach the plants more easily. Additionally, it reduces boundary layer resistance since the air does not have to travel above the plants.

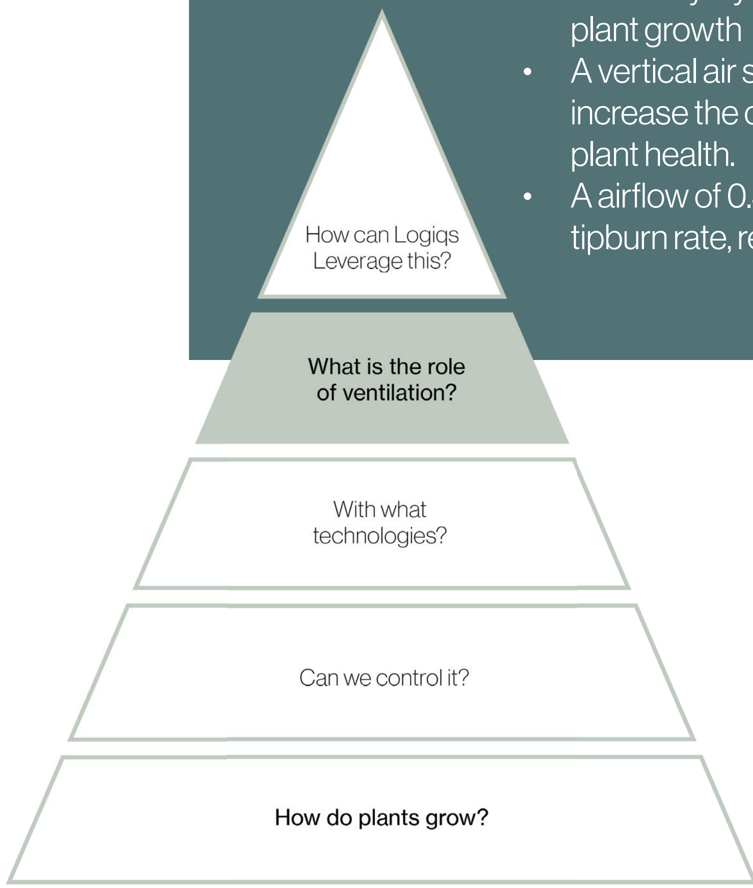
Vertical airflow creates a microclimate at the plant level, enabling better control over the overall plant environment. By blowing air evenly across every layer of the farm, it minimizes the problem of convection and ensures consistent environmental conditions. The air first reaches the plants before being warmed by the LEDs, maintaining a cooler and more stable temperature around the plant canopy.

Reducing stagnant air with vertical airflow helps prevent issues like tipburn, and provides better control over the entire farm. Integrating sensors can further optimize the system, allowing for real-time monitoring and adjustment of airflow to maintainthe best conditions on every layer.

Research by Kitaya et al. (2000) supports the benefits of vertical airflow. Their study on the effects of vertical versus horizontal air currents on transpiration rates in a model plant canopy found that at air current speeds of 0.15 and 0.25 m/s, vertical airflow resulted in evaporation rates 2 and 2.7 times higher, respectively, than horizontal airflow. Vertical airflow effectively reduces the thickness of the leaf boundary layer at the canopy surface, improving water vapor diffusion rates. Therefore, using vertically downward air currents is beneficial for high-density plant growth in closed systems.

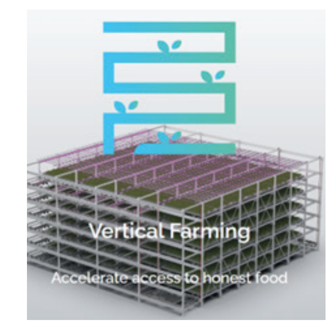
2.5.6- Conclusion

- A vetical air supply of 0.2 m/s within the boundary layer is necessary for optimal plant growth
- A vertical air supply in a vertical farm will increase the climate uniformityh and plant health.
- A airflow of 0.3 m/s will reduce the tipburn rate, resulting in healthier plants



2.6- Logiqs

Logiqs is a company that specializes in developing robotics and logistical systems for automation across three primary sectors: greenhouse automation, warehouse automation, and the vertical farming industry. In greenhouse automation, Logiqs offers an automatic mobile benching system designed to enhance the efficiency and productivity of plant handling. For warehouse automation, they have developed iCUBE, an intelligent storage and retrieval system that optimizes space and improves inventory management. In the vertical farming industry, Logiqs provides controlled environment modules, which are essential for maintaining optimal growing conditions and maximizing crop yields in indoor farming setups.



2.6.1 - Technological Advancements at Logiqs

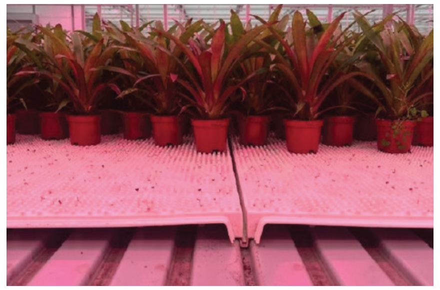
Logiqs has been innovating within the vertical farming industry since deploying their technologies in 2015. Originally known for their carrier robots that transport plants in greenhouses, Logiqs adapted these robots to move vertically, making them suitable for automated vertical farming operations.

To further penetrate the vertical farming market, Logiqs invested in research and development, focusing on creating a new growing chamber with enhanced climate control and homogeneity, known as the Controlled Environment Module (CEM). These modules are particularly used in the research sector. Designed for maximum space efficiency, the integrated CEM units can be stacked on top of each other.

The CEM offers approximately 6 square meter growing surface (3,6 m x 1,65 m), accommodating pots for automated plant growth. Each module includes an integrated control interface to manage climate parameters (temperature, humidity, air speed, CO2 levels), lighting (far red, red, white, blue spectrums), and irrigation (pH, EC, flow rates). Achieving climate uniformity, the CEM is one of the first growing chambers to adopt vertical ventilation, which blows air from beneath the plants, ensuring consistent airflow and optimal growing conditions.

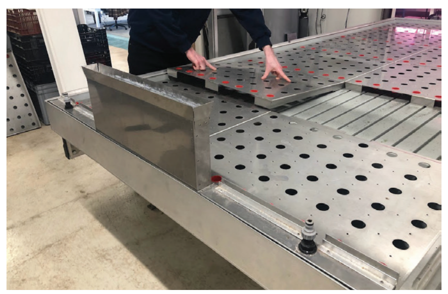
Picture 24: Logiqs' Controlled Enviroment Module (CEM)

2.6.2- Vertical Air Supply at Logiqs



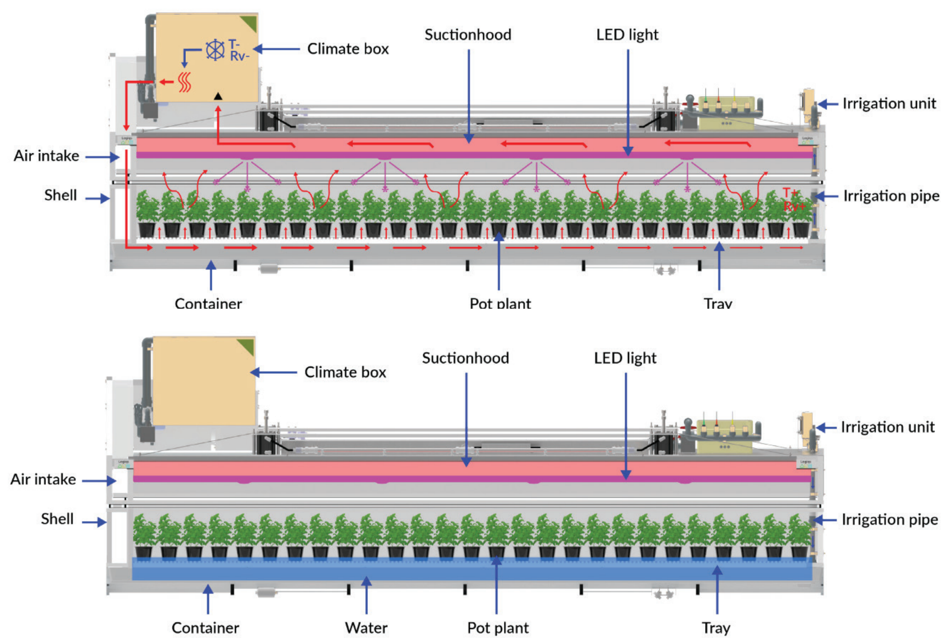
Picture 25: Vertical ventilation trays installed at flower cultivator

Logiqs has been innovating with vertical air supply within their Controlled Environment Modules (CEM), developing solutions to optimize airflow for greenhouse cultivation. Their latest venture involves collaborating with a major flower cultivator to implement a Logiqs plate that blows air beneath the plants in greenhouses. This is achieved using an in-house developed plastic tray on which plant pots are placed. The tray is perforated, allowing air to move from beneath the plant's canopy. When these trays are placed together, they create an airtight seal, and air is blown from one side, creating pressure underneath the tray that forces air out through the perforations.



Picture 26: Hydroponic trays with integrated air cavities are placed to be installed in the CEM

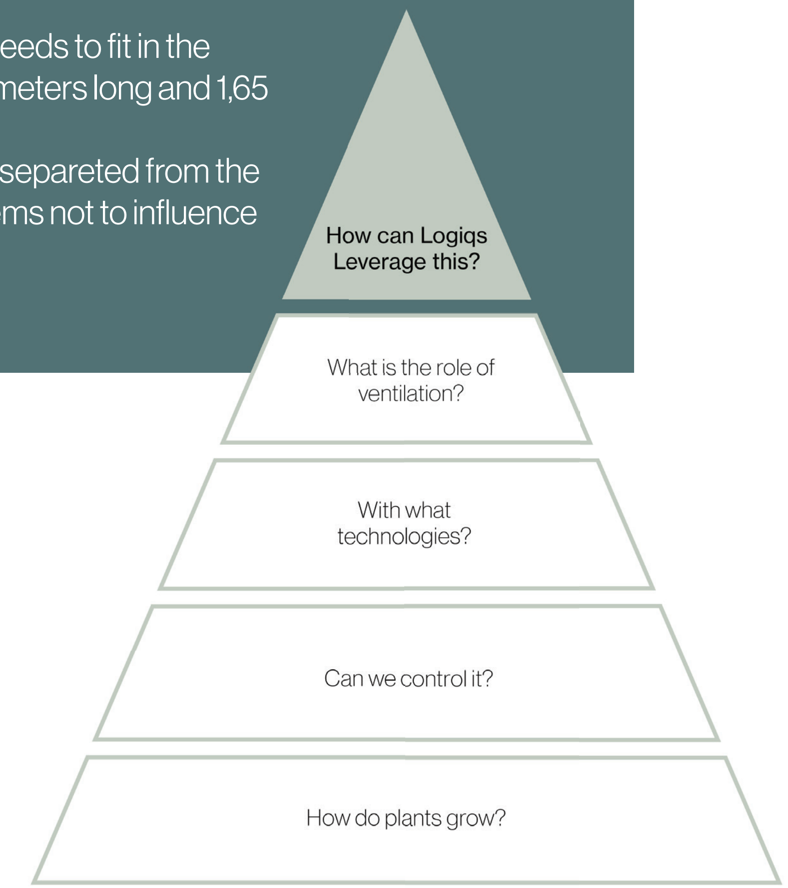
Within the CEM, air is also delivered vertically. Logiqs is currently adapting their tray to fit this system as well. They have devised various methods of delivering air, including hydroponic plates where plants can be placed and air is blown in the cavity underneath. However, these solutions have encountered challenges. One notable issue is the lack of uniformity in air supply across the entire surface. Additionally, integrating air and water in some systems leads to complications, such as the water temperature influencing the air temperature. Attempts to separate the water from the air have been made, but have not yet been successful.



Picture 27: CEM visualisation of the air supply and ebb/flow irrigation (Logiqs)

2.6.3- Conclusion

- The new system needs to fit in the CEM which is 3,6 meters long and 1,65 meters wide
- The air nees to be separeted from the water in new systems not to influence eachother.



CHAPTER THREE

PROJECT DEFINITION

The project definition phase outlines the objectives I aim to achieve and pursue. In this section, I present a list of requirements for the development of the growing trays and another set for the development of the vertical farm system.

03.

3.1- Project Objectives

The objective of this graduation project is to design a new growing tray and integrate it into a redesigned PFAL system, utilizing vertical air supply. This innovative approach aims to change climate control in the vertical farming industry, positioning Logiqs at the forefront of this transition.

The new farm offers significant advantages for urban implementation, particularly in vacant urban spaces. This design allows for the establishment of vertical farms in existing buildings without requiring extensive infrastructural modifications.

The advanced climate control system, including microclimate creation at the plant level, ensures that the growing environment is precisely regulated. This self-contained system reduces reliance on the building's existing HVAC (Heating, Ventilation, and Air Conditioning) infrastructure, simplifying installation and operation.

3.1.1- 3 Design Objectives

1. Design of a New Growing Tray
Develop a growing tray that supports vertical air supply, ensuring uniform air distribution across the entire plant surface. This design will facilitate better environmental control directly at the plant level.
(Chapter 04. Development Growing Tray)

2. Redesign of the Vertical Farm System
Integrate the new growing trays into the existing vertical farm layout. The redesign will optimize the system to fully leverage the benefits of vertical air supply, enhancing overall farm efficiency.
(Chapter 05. Development PFAL)

3. Integration with Controlled Environment Module (CEM)
Incorporate the vertical ventilation system into Logiqs' CEM. This integration aims to achieve more uniform and precise climate control, particularly for research and development purposes.
(Chapter 07. Discussion)

3.2- List of Requirements

The morst important requirements can be found in table X. The requirements are derived from prvious chapters. These are presented in the MoSCoW format (M- **Must** have, S- **Should** have, C- **Could** have, W-Won't have) each category denoting a priotization category.

The list is subdevided into my 4 objectives.

3.2.1 - Growing Tray

Must

- Provide vertical ventilation of 0.2 m/sec.
- Feature a design that keeps water and air channels separate.
- Maintain a maximum 5% difference in airflow speed over 3.6 meters.
- Use reflective materials to reflect 95% of light during germination.
- Include an irrigation system tailored for basil.
- Weigh under 16 kg for easy handling.
- Have washable surfaces for hygiene in controlled environments.

Should

- Be compatible with current Controlled Environment Modules (CEMs).
- Be versatile enough to grow various crops, not just basil.
- Aim for a cost below €50 to be affordable for small to medium-scale growers.

Could

- Integrate sensors for real-time monitoring of temperature, humidity, and nutrient levels.
- Offer modular components for customization and scalability.
- Use eco-friendly materials to enhance sustainability.

3.2.2 - Farm system

Must

- Allow efficient management by manual labor and gradual automation.
- Feature a modular structure for easy assembly, disassembly, and adjustment.
- Control climate, lighting, and irrigation independently for each layer.
- Utilize 90% of the floorplan for growing space efficiency.

Should

- Include an interface for controlling operations and collecting data across all farm layers.
- Prioritize space efficiency and scalability for flexible expansion.

Could

- Integrate robotics for automation as needed.
- Use renewable energy sources or energy-efficient systems.
- Support vertical farming techniques for increased productivity.

CHAPTER FOUR

DEVELOPMENT GROWING TRAY

In this chapter, I will delve into the development and design process of the growing tray. Initially, I brainstormed and generated seven ideas, three of which were further refined into detailed concepts. One of these concepts was ultimately selected for further development through an iterative process.

04.

4.1- Idea Development

After a structured brainstorming session with the entire R&D vertical farming department, ideas were generated using the "why, who, where, when, what, how" method. These questions were posed to explore ways to grow plants indoors at various scales, including a single plant, a row of plants (1D), a surface of plants (2D), and stacked surfaces (3D). This approach helped the team think beyond the Controlled Environment Module (CEM) they had been focused on for a long time.

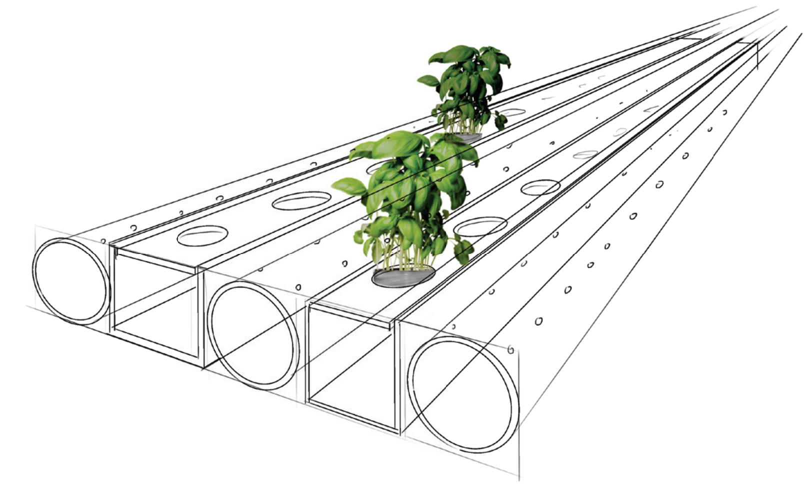
Before the idea generation process, I presented a patent research on air distribution in other industries. By drawing analogies from these diverse fields, I aimed to provide a broader perspective and inspire innovative thinking within the team. This methodical and expansive approach encouraged creative solutions and new concepts for indoor plant growth at different scales, enhancing our overall design and development strategy.

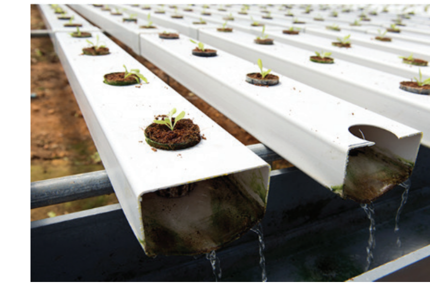
Picture 28: Results of the brainstorm sessions at Logiqs. Ideas are clustered.

These findings were clustered and translated in 7 Ideas that I presented:

4.1.1- Tubes

Tubes are placed in fixed positions within the farm. Gutters are then placed between these tubes, ensuring that the plants receive air from both sides. Nutrient Film Tech nique is used for the irrigation. The uniformity of the air is achieved by varying hole size and distance.

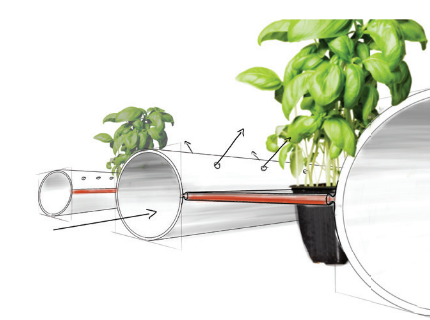




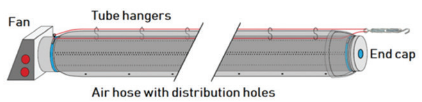
Picture 29: Gutters are often used in the hydrponic horticulutre industry. Many machines have been developped to automate the growing process in gutters.

4.1.2- Knecks

Tubes are designed to float on a water basin and are connected to plates where the plants are mounted. These tubes serve a dual purpose: they support the floating structure and distribute air. The system is modular and can be clicked together for easy assembly and expansion. Deep Water Culture (DWC) is used for irrigation, providing a nutrient-rich solution to the plant roots. Air uniformity is achieved by varying the size and distance of the holes in the tubes



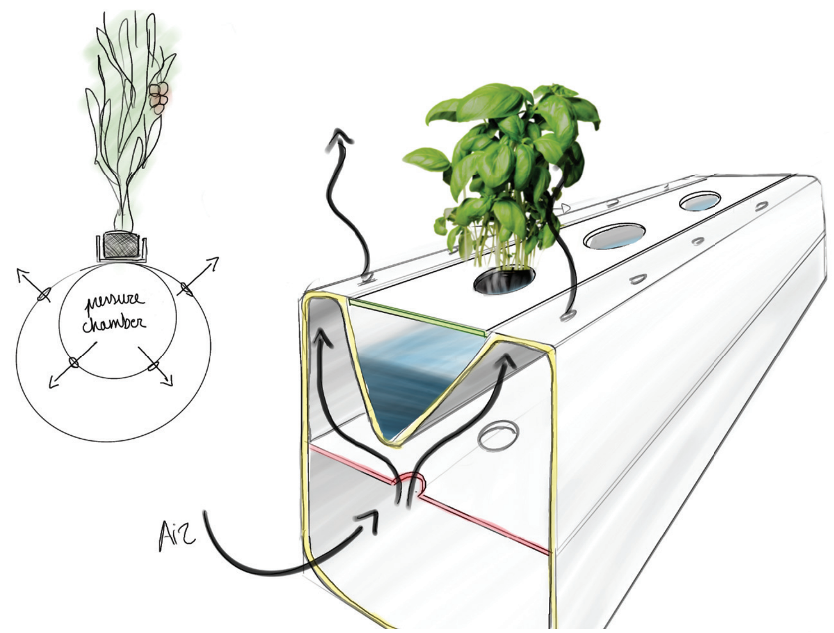
Picture 30: Side view of the knecks idea showing the air distribution.



Picture 31: Kubo's Patent for double hose with varying hole pattern

4.1.3- Pressure Chamber

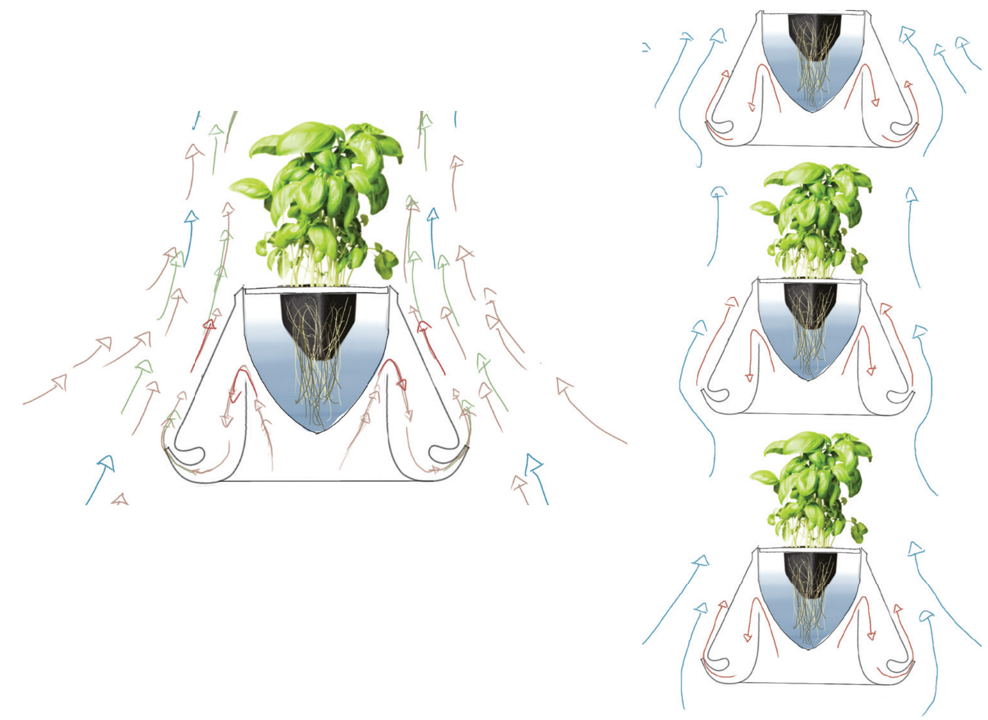
A gutter that doubles as a ventilation hose employs the principle of a pressure chamber to distribute air evenly. The air channel is divided into two parts: the lower part, where air is blown in laterally, creating overpressure, and the upper part, where the air is distributed to plants on both sides. This design ensures uniform airflow across the growing area. Kubo recognized the potential of this principle in the greenhouse industry and patented a double-hose design that uses one hose as a pressure chamber and the other for air distribution.



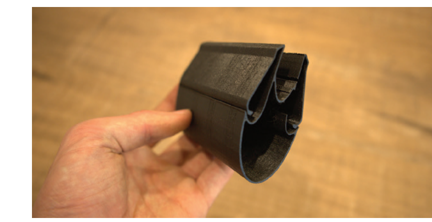
4.1.4- Dyson

The Dyson-inspired idea builds upon the pressure chamber concept by incorporating a new principle. When air is accelerated over a wing, it creates an underpressure buildup at the wing's end, further accelerating the air and drawing in additional outside air into the existing airflow. This design, based on Dyson's bladeless air blower patent, can accelerate the air coming out of the blower up to 15 times.

Implementing this principle in vertical farming would generate significant air movement within the farm. The system would accelerate air from the lower layer to the upper layer if the gutters are stacked upon one another.



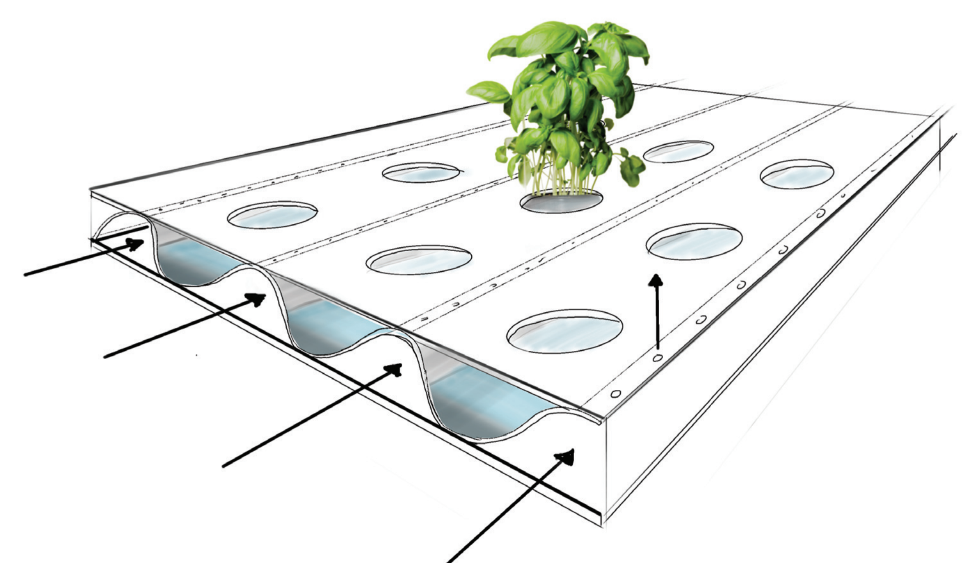
Picture 32: CFD of intersection air wing with air acceleration



Picture 33: 3D print of gutter with inlcuded ventilation

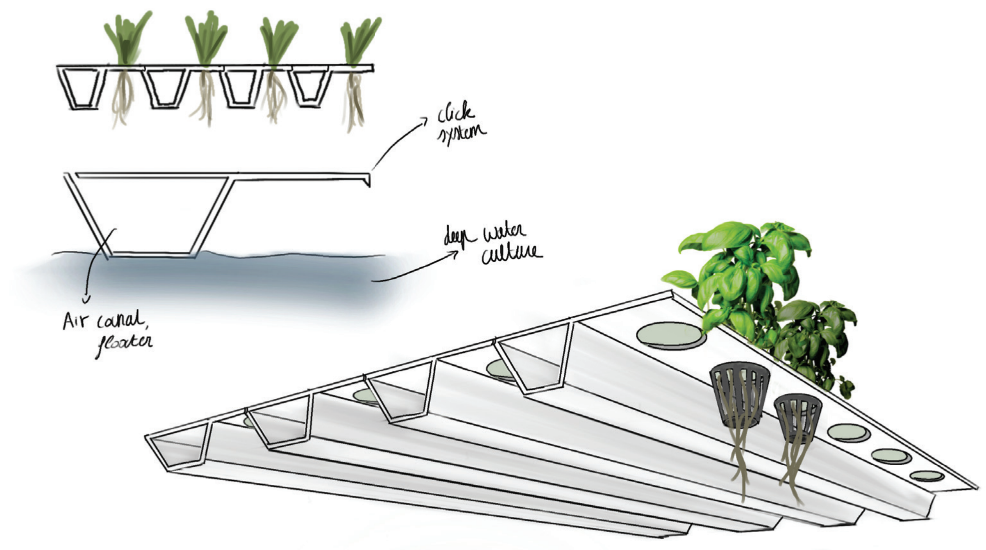
4.1.5- Roof

The roof concept utilizes a corrugated sheet with two plates mounted on it—one on the top and one on the bottom. The corrugated sheet creates alternating cavities, with one cavity designated for air distribution and the other for water distribution. The air is distributed uniformly by varying the hole pattern in the air channels.



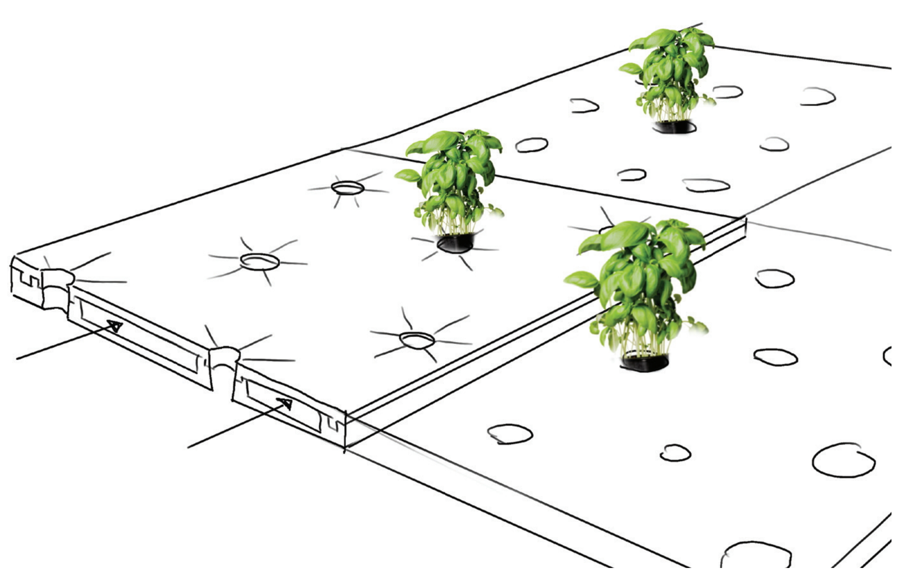
4.1.6- Click Gutters

The click gutters system is a modular setup similar to the K'NEX assembly system, where the ventilation pipes also serve as floating bodies. Each part includes a ventilation tube on one side and a plate on the other that supports the plants above the water while preventing light from reaching the water. These parts can be clicked together to form a cohesive unit and then placed into a water tank using Deep Water Culture (DWC) irrigation.



4.1.7- Plates

The plates consist of two injection-molded parts similar to the plates Logiqs has already developed. These plates connect to each other, creating a floating body. They contain holes through which the plants pass, allowing the roots to extend into the water. Turbulent air is blown into the hollow body to create overpressure, and additional holes are strategically placed around the plant to ensure air distribution all around the plant's stem.

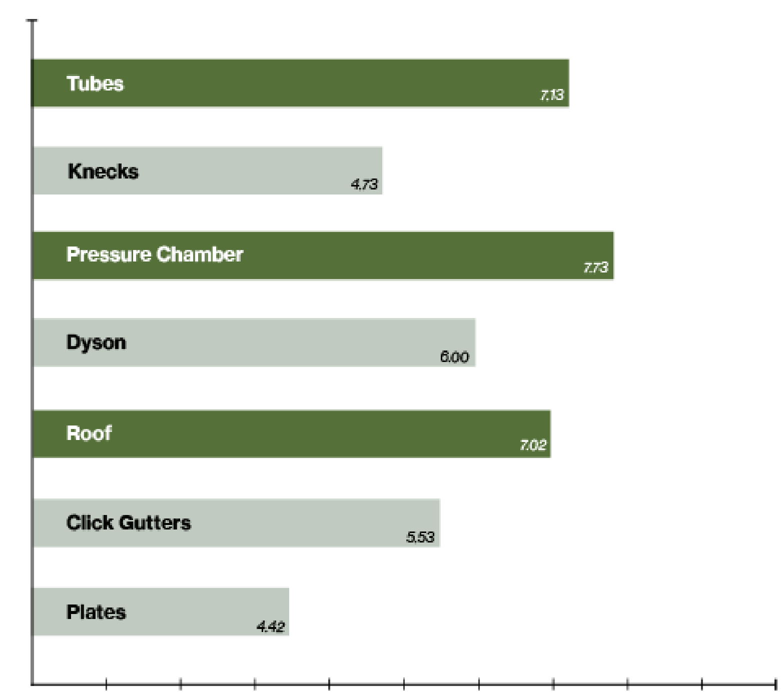


4.2- Concept Development

The seven ideas were presented to the participants, and each conducted a SWOT analysis for every idea. A SWOT analysis is a strategic planning tool used to identify the Strengths, Weaknesses, Opportunities, and Threats related to a particular concept or project. This method ensured a balanced evaluation, considering both the positive and negative aspects of each idea. Each participant's SWOT analysis was submitted individually to avoid influencing each other's evaluations. This approach ensured an honest and independent assessment of each idea. Each participant's SWOT analysis was submitted individually to avoid influencing each other's evaluations. This approach ensured an honest and independent assessment of each idea.

Picture 34: 3 examples of the filled in SWOT sheets after the presentation to the R&D Vertical Farm department

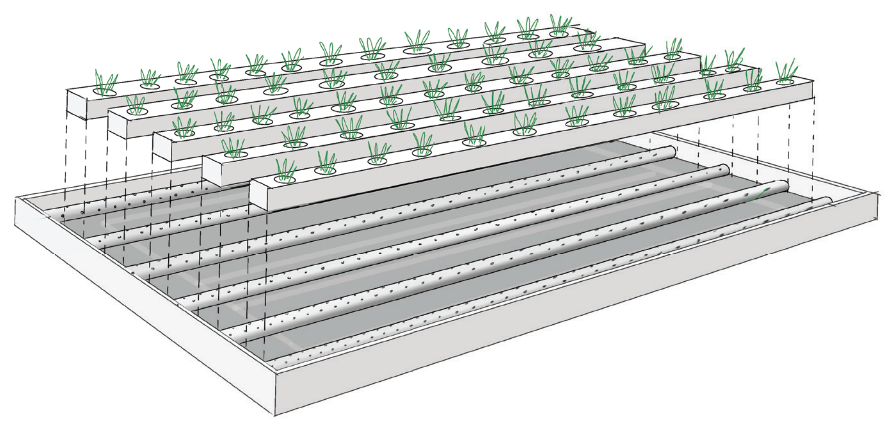
The SWOT analysis serves as a method to evaluate the ideas, not to chose an idea. Therefore, each participant rated the ideas on a scale of 1-10 based on the following aspects: user-friendliness, uniformity of air distribution, simplicity, hygiene, and personal preference. These ratings helped further assess the feasibility and attractiveness of each idea from various perspectives, providing a comprehensive evaluation framework for decision-making.



*I decided to conceptualise tree designs wth the higherst score. Tubes, Pressure Chamber, and the Roof.

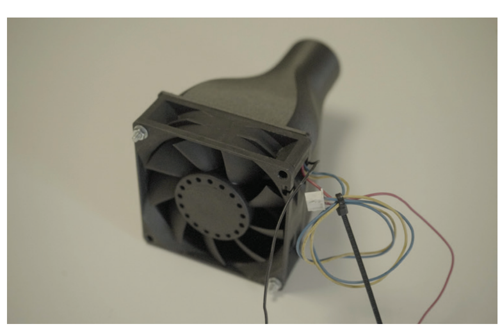
4.2.1- Tubes

The first idea I explored was the tube system. In this concept, tubes are mounted as fixed structures within the farm. These tubes feature a hole pattern designed to ensure even airflow distribution throughout the entire farm. The plants are positioned between these tubes, either in gutters for Nutrient Film Technique (NFT) irrigation or in a basin for Deep Water Culture (DWC) irrigation. Both irrigation methods will be considered for this concept.



Initial Setup

To start, I needed to decide on the hole diameters, patterns, and the diameter of the air pipes. After careful consideration, I chose a pipe diameter of 50mm. This decision was made to balance optimal air distribution with space efficiency for the plants. Simulating the perforations in terms of pattern and diameter is challenging due to the turbulent behavior of air in a perforated pipe. Therefore, practical testing was deemed the best approach.



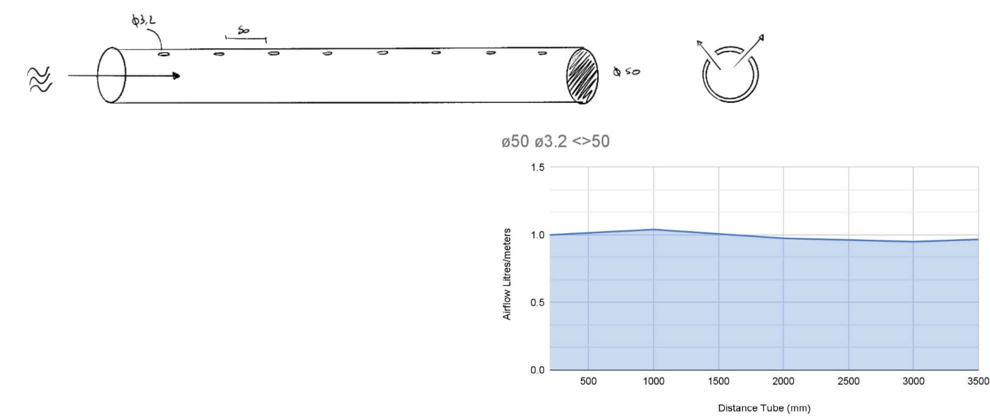
Picture 35, 36: 3D printed mount for venitlator to tube, Installed mount on tube

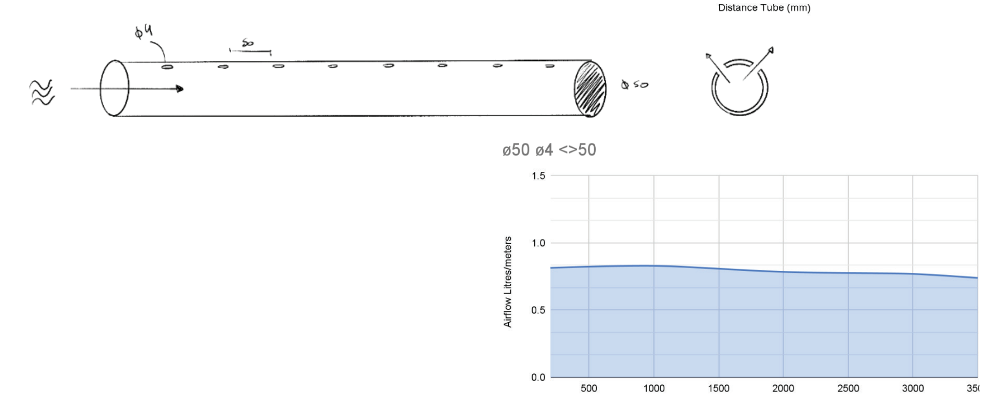
Testing Process

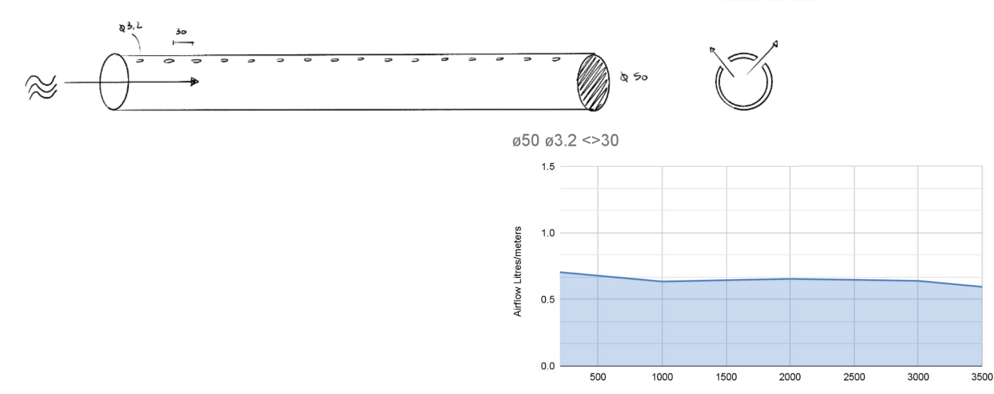
First, I 3D-printed five mounts to connect the ventilators to the pipes. These ventilators are connected to an external power supply that I can regulate. Using 3.6-meter-long pipes with a 50mm diameter, I perforated them to test different configurations:

Pipe	Perforation Distance	Perforation Diameter
1	50 mm	3.2 mm
2	50 mm	4 mm
3	30 mm	3.2 mm

The following graphs illustrate the results of these tests:

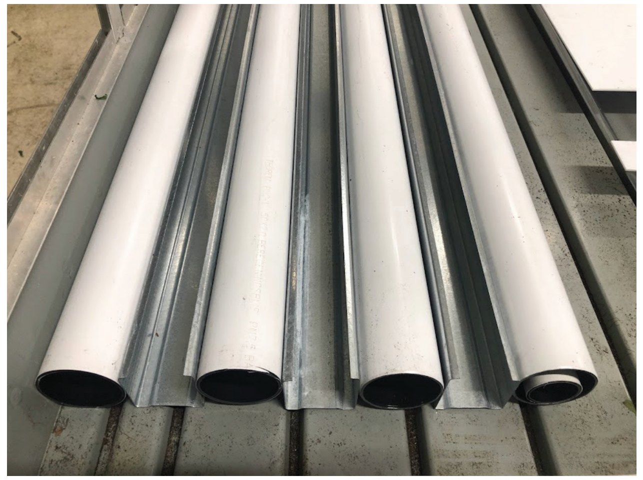


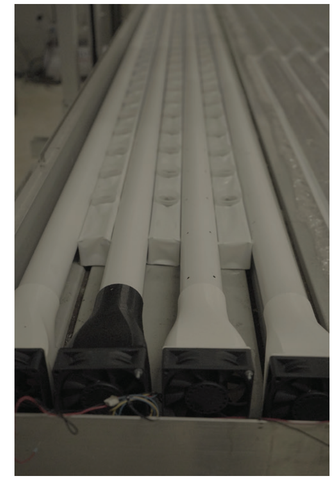




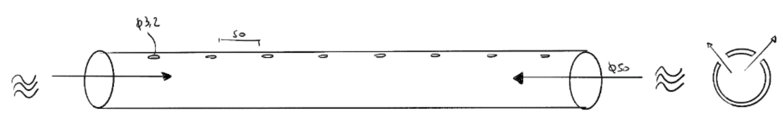
From these tests, I concluded that the configuration with 3.2mm holes spaced 30mm apart was the best for a 50mm pipe diameter over a length of 3.6 meters.

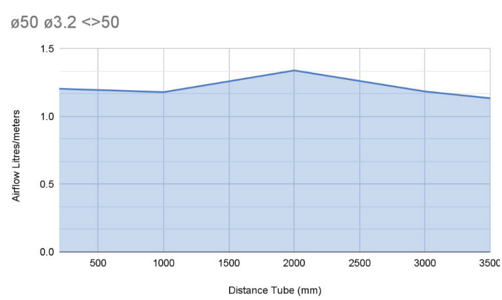
Picture 37, 38 tubes with ventilators and gutters placed inbetween with plant holders, Tubes and gutters alternating



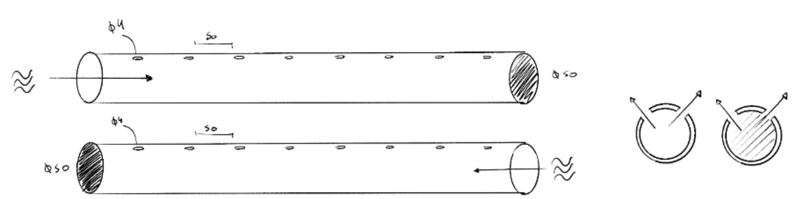


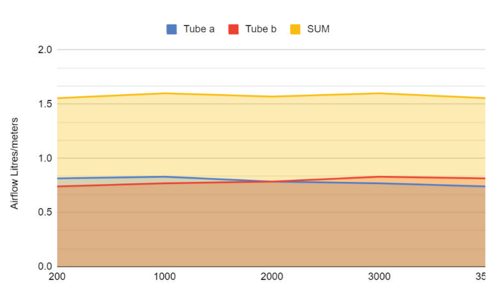
Next, I tested what would happen if the pipe was not capped at the end and what would occur when air was blown from both sides of the pipe. The results showed that a capped pipe was the most efficient, allowing pressure to build up within the pipe.





Another idea was to have two pipes next to each other, one blowing from one side and the other blowing from the opposite side. In theory, this setup would sum up to achieve perfect uniformity in airflow distribution.





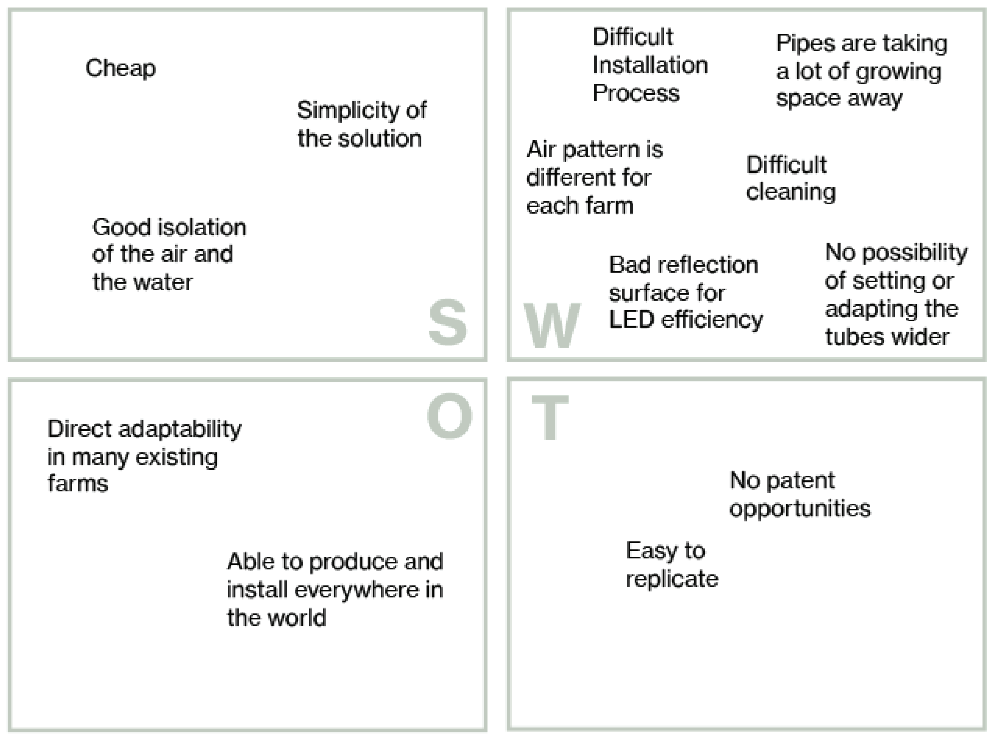
CEM test

With all this in mind, a test was conducted in the Controlled Environment Module. Fifteen pipes were installed across the entire surface, with airflow conducted through them. Plants were placed in plastic trays between the pipes, and arugula lettuce was grown in this setup. Water was pumped in and out of the basin where the whole system was installed, utilizing an Ebb and Flow irrigation system.

Picture 39, 40, 41: Rucola germinating vertically, Installation of the perforated pipes, Rucola placed in plastic trays inbetween the tubes

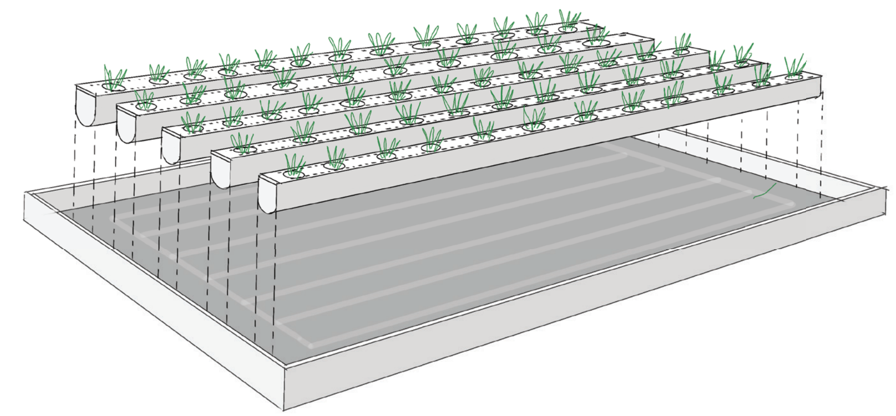
The installation of the system in the Controlled Environment Module demonstrated how this idea would function in a broader context. The test highlighted both the complexity of the installation process and the potential effectiveness of the design. Since the plastic trays rested gently on the pipes, they acted like rails, allowing the trays to move smoothly along the pipes. This aspect of the design showed promise for facilitating easy maintenance and adjustment of plant positioning. Overall, the test provided valuable insights into the feasibility and scalability of the tube system for uniform airflow and efficient irrigation in a controlled environment.

Picture 42: SWOT Analysis Gutters



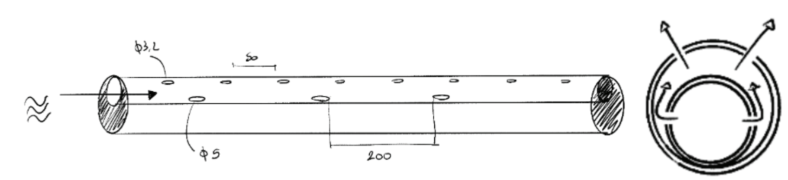
4.2.2- Pressure Chamber

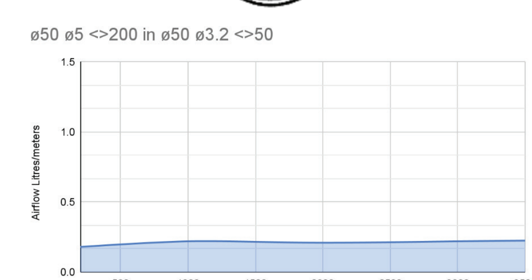
The second idea I explored was the potential of creating a gutter with an integrated air canal. This gutter would contain two separate air channels: one for creating overpressure along the entire length and another for distributing air from beneath the plant. The gutters need to be 3.6 meters long, as it is challenging to click them together along their length. Since each gutter is separate, they can be placed further apart as the plants grow.



Initial testing

The first test aimed to examine the principle of a pressure chamber. For this, I used a perforated pipe with 8mm holes spaced 200mm apart. This pipe had a diameter of 30mm and was placed inside another pipe with 3.2mm holes spaced 50mm apart. Both the inner and outer pipes were capped, and a ventilator was used to blow air into the middle pipe (the pressure chamber). The following graph shows the airflow distribution:

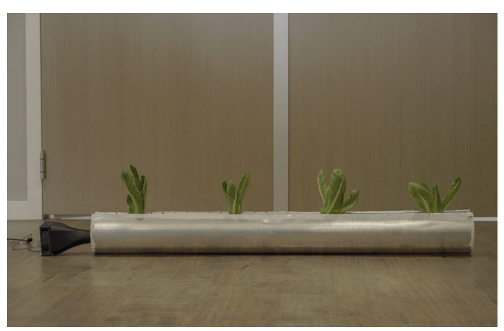


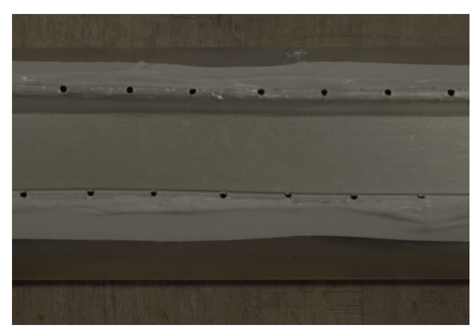


The results indicated that the airflow was very consistent and uniform. However, the overall airflow was significantly reduced due to the double chambers, which introduced additional drag.

Prototype Development

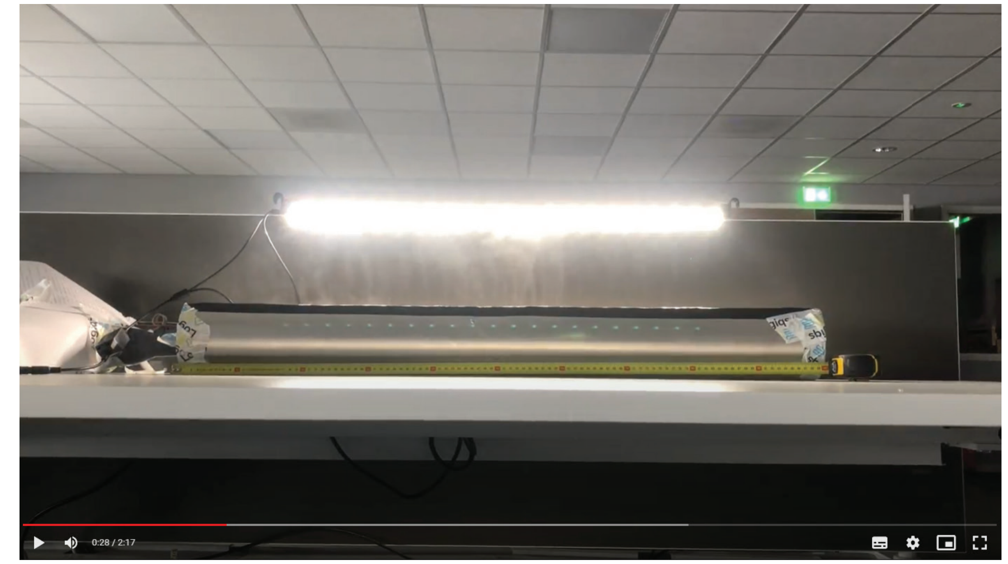
Following the initial test, I developed a second prototype to further explore this concept. The prototype was 800mm long and made of aluminum, which I TIG welded together. The design was modified to ensure that air would be blown into a central pressure chamber, then flow down through holes into the outer cavity of the gutter. As the air flowed on both sides and the internal area of the sides decreased, the air was accelerated into the plant canopy.





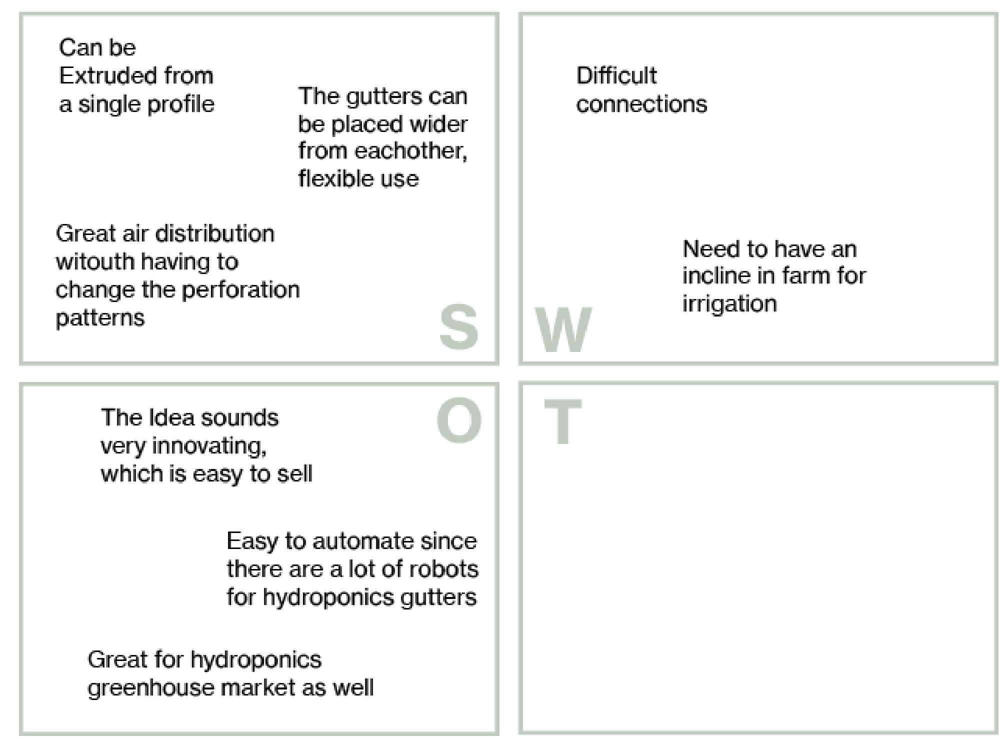
Picture 43, 44, 45: Hollows gutter prototype, Prototype with plants and venitlation, Perforations from the top view of the gutter

To test the airflow within the prototype, I introduced smoke into the central part of the gutter and installed a ventilator. With appropriate lighting, I observed how the air distributed over the short length. Initially, the air filled the central pressure chamber, then gradually moved into the outer cavities, coming out of the perforations first at the center. After approximately six seconds, the air was evenly distributed over the entire length.



Picture 46: Experimentation with smoke machine blowing air in the gutter. With Led behind to make the smoke visible

This design showed significant potential because it can be easily extruded, making it cost-effective. I had meetings with various extrusion companies in the Netherlands. Primo Plastics was identified as a possible partner to create the mold for the injection molding process and handle manufacturing. They have previous experience in the horticulture technology sector, producing clickable gutters.

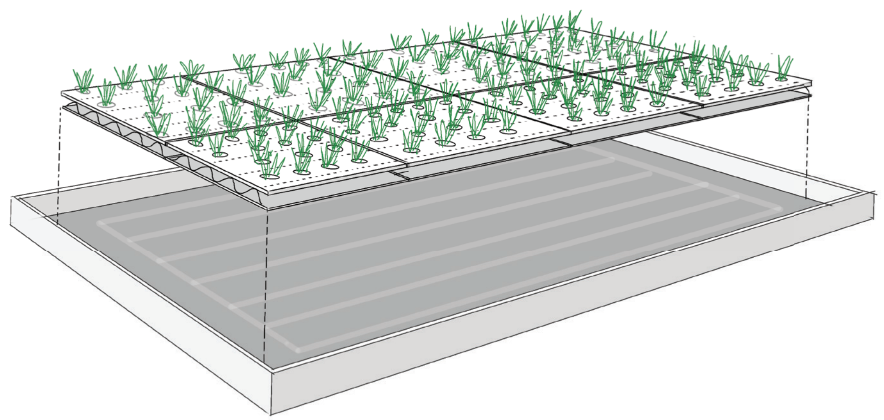


Picture 47: Swot Analysis Pressure Chamber

4.2.3- Roof

The last idea I investigated was the roof concept. This idea was developed by examining the growing trays used in vertical farms. Typically, these trays have a 2D surface on which plants are placed to grow. The flat surface of the trays not only makes them easy to handle but also reflects light from the LEDs better, enhancing energy efficiency.

Initially, I envisioned creating this system with pipes mounted together to cover the entire Controlled Environment Module (CEM) with trays, while still being manageable. For practicality, the system needed to be modular, with trays that could click together.

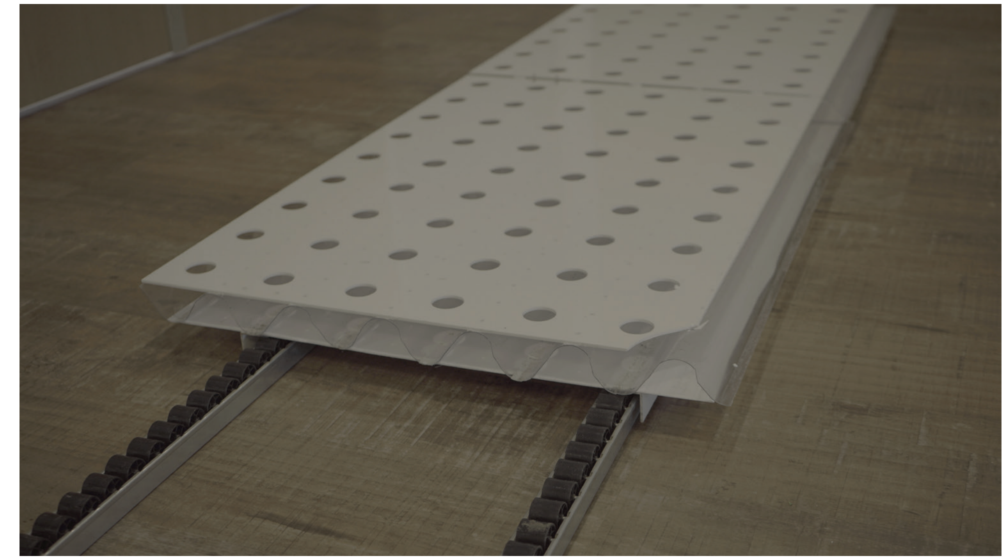


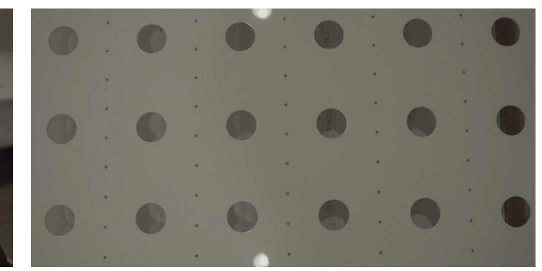
Prototyping

I began experimenting with corrugated sheets, often used for roofing. Their wave-like design creates alternating channels, which can be used separately for water and air. These corrugated sheets were mounted with a plexiglass sheet on top and another sheet on the bottom. This setup allowed me to laser-cut the ventilation and plant pattern on the sheet. I selected a 3.2mm hole pattern spaced every 30mm for optimal air distribution.

To improve tray handling, I decided to let them rest on a roller track, enabling the trays to click together and be pushed in the system like drawers. To keep the trays in place, holders were installed beneath them to prevent lateral movement.

Picture 48, 49: Hollows gutter prototype, Prototype with plants and venitlation, Perforations from the top view of the gutter





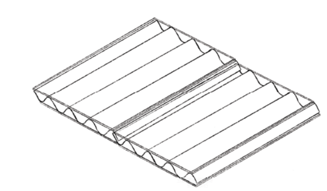
Picture 50, 51, 52: Two connected trays on roller tracks, Corner Brackets for stability, Top view of holes for plants and holes for air

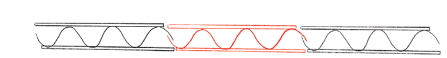
Modularity

There are two ways to connect the trays to one another, ensuring flexibility and ease of assembly in the vertical farming setup.

Side-by-Side Connection:

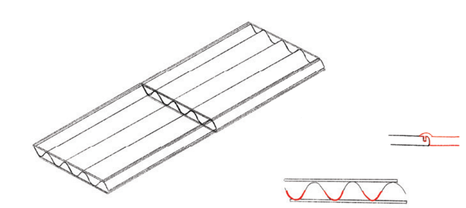
The first method is straightforward. Trays are placed next to each other and connected. This method allows them to be easily slid into one another, as illustrated in Picture x. This approach simplifies the assembly and disassembly process, making it user-friendly and efficient for routine maintenance and plant management.



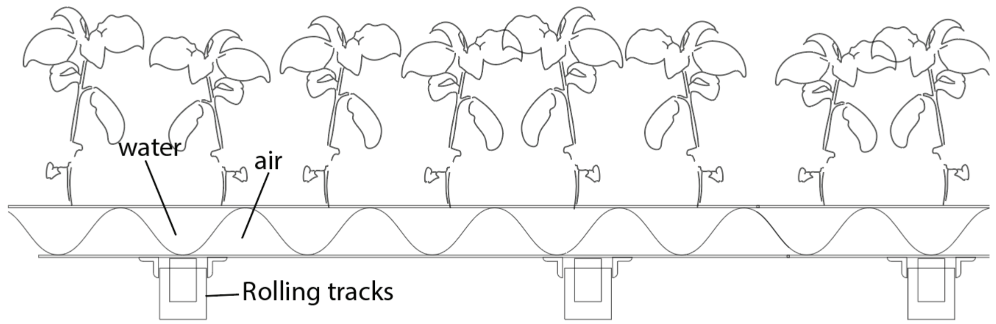


Channel Extension Connection:

The second method involves extending the channels, which is more complex because it requires creating a water and airtight seal. Picture x shows this setup. Various techniques were tested to hold the trays together securely, including the use of magnets, rubbers, and click systems. Ultimately, I decided to pursue a design where the end of one tray (male part) is inserted into the end of the next tray (female part) using rubber seals. This method provides a more secure connection, ensuring both water and air tightness. Since the rolling tracks will be angles at a 3 degrees, the water will run down the channels like roof tiles shoven into eachother.



Picture 53: Side view of growing tray on rolling tracks



Picture 54: SWOT Analysis Roof

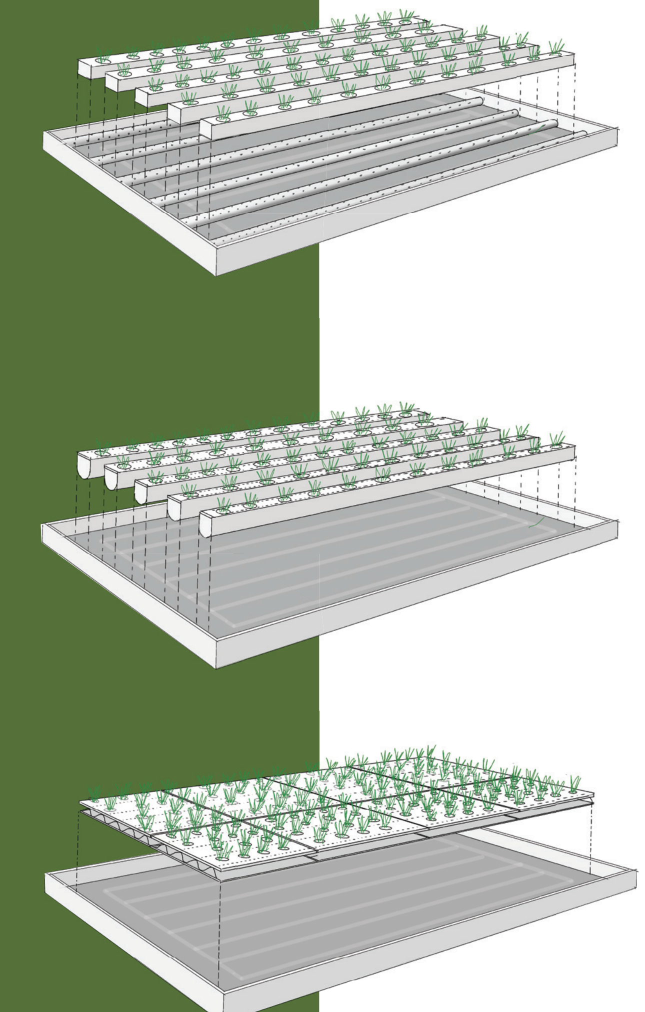
S	W
Easy to handle for mass production Space efficient Great light reflection on trays	Difficult connections Producability Need to have an incline in farm for irrigation
O	**T**
Patent potential Potentially usable for DWC irrigation Potentially usable for DWC irrigation	Too much change to inplement this in existing farms

While the tree options are valid to persue, I decided to focus my project on the roof. I still believe that the tw other conecpts holds a lot of potential, each in their own way, and I would advise Logiqs to look ito it.

I decided this since the Tubes is a concept that has complications in it's versitility.

The Pressure Chamber has great potential however, it is less pratical in Vertical Farm systems. I would see this system be implemented more easily in greenhouses.

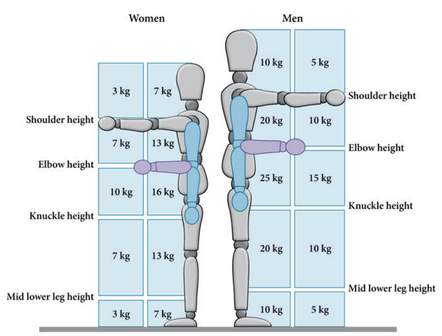
The Roof gives me the opportunity not only to work on a growing tray, but also to design a new PFAL which makes the project more interesting.



4.3- Ventilated Growing Tray

To thoroughly test the modular design, I decided to create a new prototype and fabricate four units to connect and evaluate for uniformity and water leakage. The trays were reoriented to fit within the Controlled Environment Module (CEM), and the plant configuration was redesigned for optimal space efficiency.

Key design changes included adding rubber strips to the bottom part of the trays to minimize air leakage and extending the male part of the tray to 130mm to ensure no water leakage. The final trays are each capable of holding up to 54 basil plants. The trays feature 9 ventilation canals and 9 irrigation canals. Each basil plant and holder weighs 53 grams. This is 2.82 kg in plant massa. A fully loaded plant tray weighs about 12 kg. The plant tray will be held on knuckle height, which according to the Healthy and Safety Authority is acceptable for men (25 kg), and woman (16kg) (picture 1).

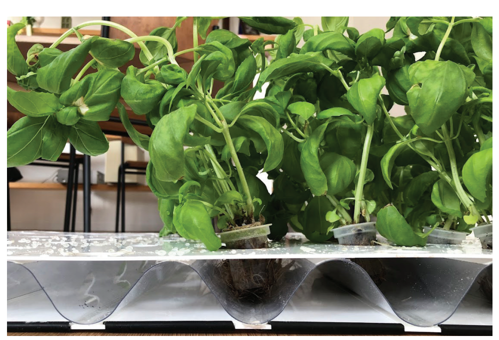


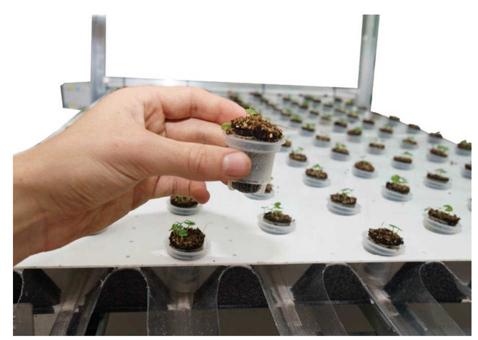
Picture 55: HSA Manual Handeling (Guide to the Safety, Health and Welfare at Work, 2006)

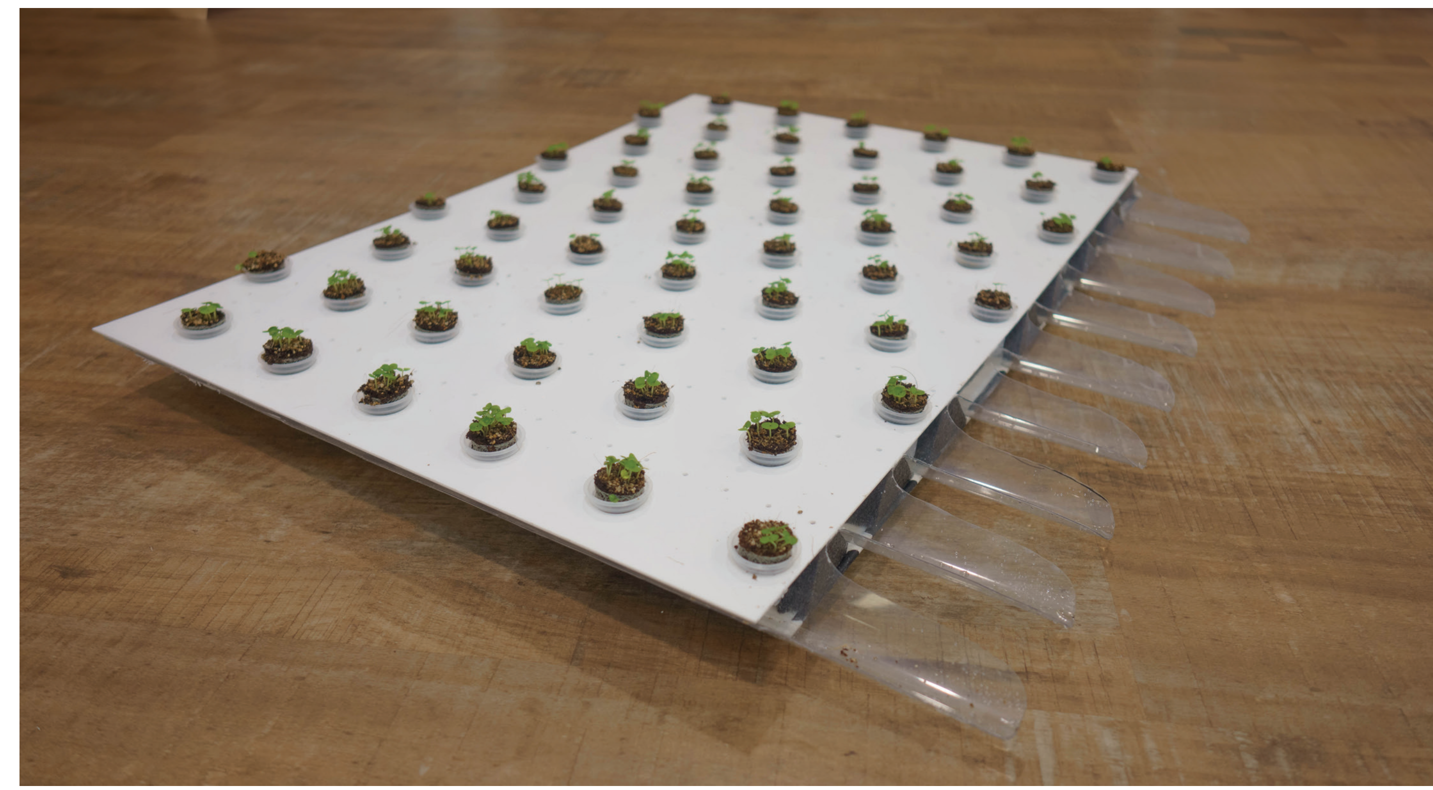
By connecting the prototypes, I was able to test the uniformity of air distribution and the effectiveness of the water-tight seals. The changes made to the design, including the use of rubber strips and the extended male parts, contributed to improved performance, ensuring a better connection and efficient operation in the vertical farming setup.

The Basil plants are grown in coco substrate that is placed in plastic plugs that can be inserted in the growing tray.

Picture 56, 57: Fully grown Basil plant (two months old) in the growing tray, The growing tray inserting a plant plug







Picture 58: Final Design of the Growing Tray

CHAPTER FIVE

DEVELOPMENT PFAL

With the growing tray developed, I will now delve into the design process of the farm that incorporates the tray, maximizing its potential. I explored various solutions for different aspects of the farm, summarizing them into a morphological matrix. This matrix helped me determine the final design of the farm, for which I built a prototype.

05.

5.1- Exploring Market and New Ideas

This chapter aims to map out the subfunctions within a vertical farm, providing a detailed look at how Plant Factories with Artificial Lighting (PFALs) currently operate. By examining these subfunctions, we can integrate existing market solutions with new ideas to optimize the overall system.

The subfunctions cover essential components such as lighting systems, irrigation methods, air distribution, climate control, and automation technologies. Each subfunction will be discussed in terms of its role and current market implementations, as well as potential innovations.

In the next chapter, these subfunctions will be introduced in a morphological chart, enabling us to explore various configurations. This chart will help identify the most effective design direction for our vertical farming system by combining different subfunctions into viable solutions.

5.1.1- Tray Modularity

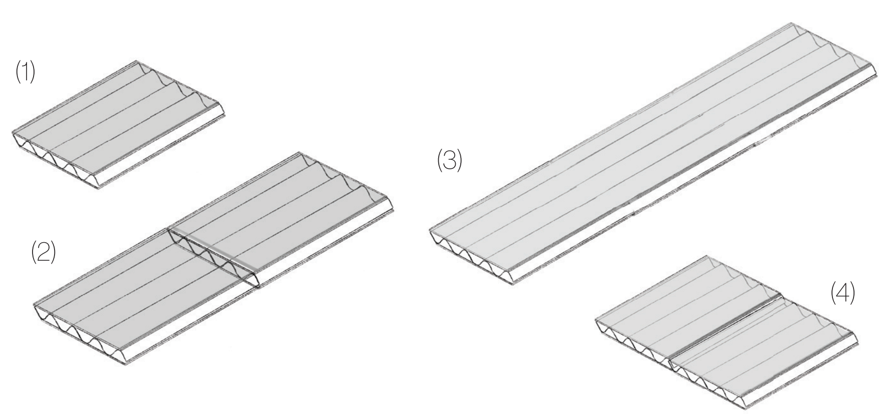
I decided to proceed with the corrugated roof concept, which offers four variations of modularity. Each variation offers distinct advantages in terms of installation, maintenance, and scalability.

1. Single Tray: Each tray has its own ventilation input, allowing for independent control and easy handling.

2. Single Long Tray: A tray that is 3.6 meters long, covering the entire length of the vertical farm, ensuring continuous airflow and water distribution witouth leakage.

3. Connectable Lengthwise Tray: Trays that can be connected lengthwise, providing flexibility in adjusting the length of the growing area.

4. Connectable Widthwise Tray: Trays that can be connected widthwise.



5.1.2- Stacking system

There are several ways to stack the trays upon one another.

1. Wall-Mounted Stacking: Trays are stacked by connecting them to a wall using L brackets on both sides. This method easy access for maintenance and harvesting, and requires less material.

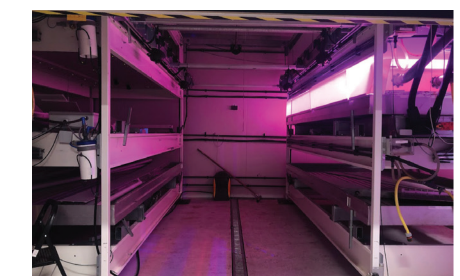
2. Racking System: Trays are stacked into a open racking system.

3. Modular Stacking System: Each tray can be placed upon the other, allowing for flexible and scalable configurations. This method is suitable for smaller operations or modular setups.

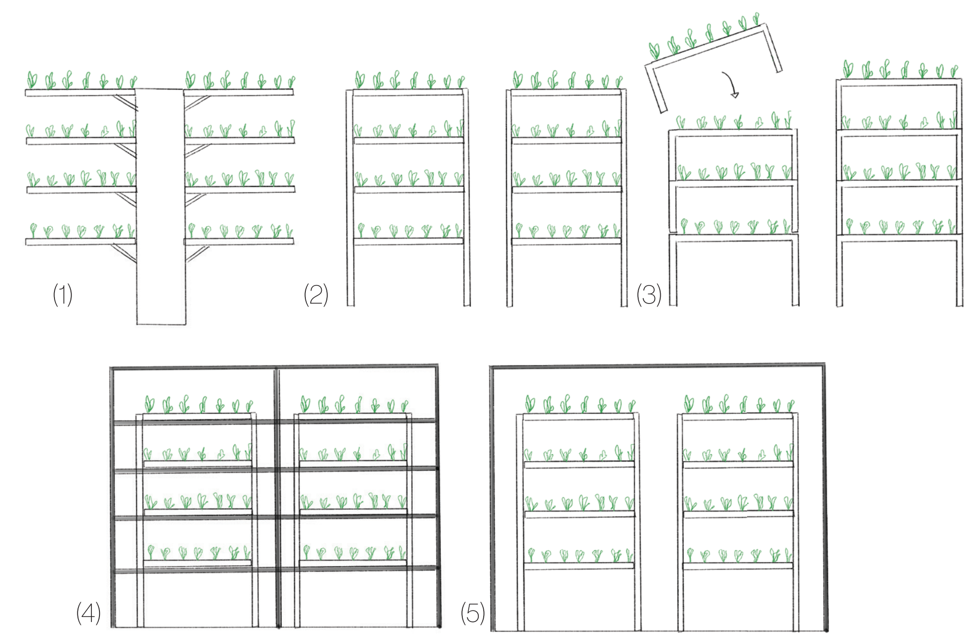
4. Climate-Regulated Room: Trays are stacked in a racking system within a climate-regulated room (see Picture 59). Most PFALs are built this way.

5. Isolated Layer Racking System: Trays are stacked in a racking system where each layer is isolated to provide more regulated climate control. Logiqs' PFAL is built this way, enabling them to run different tests with varying climate recipes (see Picture 60).

Picture 59: PFAL trays in a climate-regulated room ()



Picture 60: Logiqs' isolated layers racking system



5.1.3- Vertical Transport

The vertical transport of trays in a vertical farming setup can be managed in several ways to facilitate movement up and down within the system. This is the way the trays are being placed within the farm.

1. Manual Handling: Trays can be moved by hand. This method is suitable for smaller operations where the number of trays is manageable without the need for automated assistance.

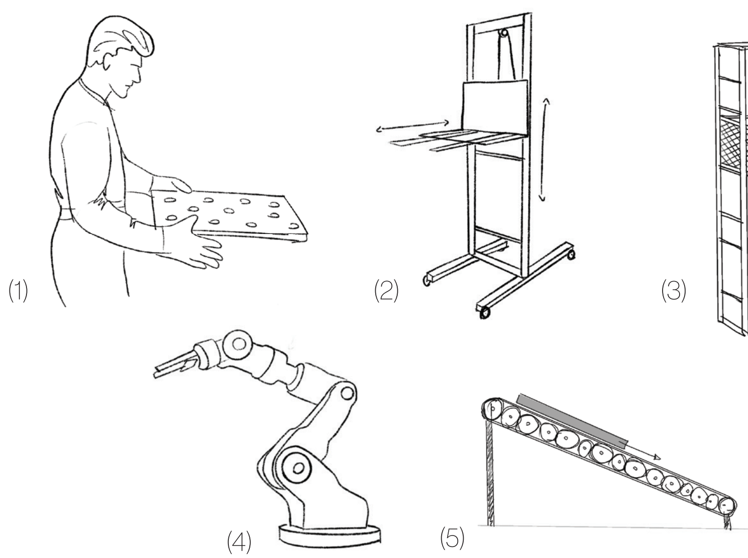
Picture 61: Plenty's Robot arm in their Compton farm

2. Robotic Lift Arm: A robotic lift arm can automate the process, moving trays up and down with precision. This method is ideal for larger operations seeking to minimize labor and improve efficiency.

3. Lift System: An integrated lift system can be used to transport trays between different levels.

4. Robotic Arm: A robot arm moving in 3D able to reach various angles. This solution is very versitile since the arm can do other tasks as well (Picture 61)

5. Sliding Rails: Using gravity to slide the trays down to their selected level.



5.1.4- Horizontal Transport

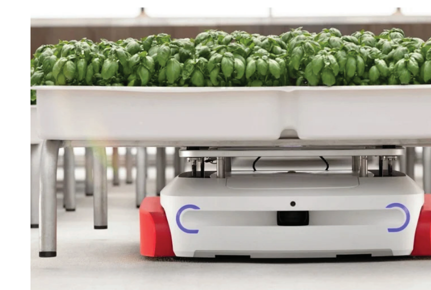
Transporting trays horizontally over the length of the farm's layers:

1. Floating Bodies: Specifically in Deep Water Culture systems, trays can float and be pushed across the water surface. (Picture 62)

Picture 63: Floaties trays in a Deep Water Culture farm (Dry Hydroponics)

2. Rails: Trays can be placed on rails, allowing them to slide smoothly across the growing area.

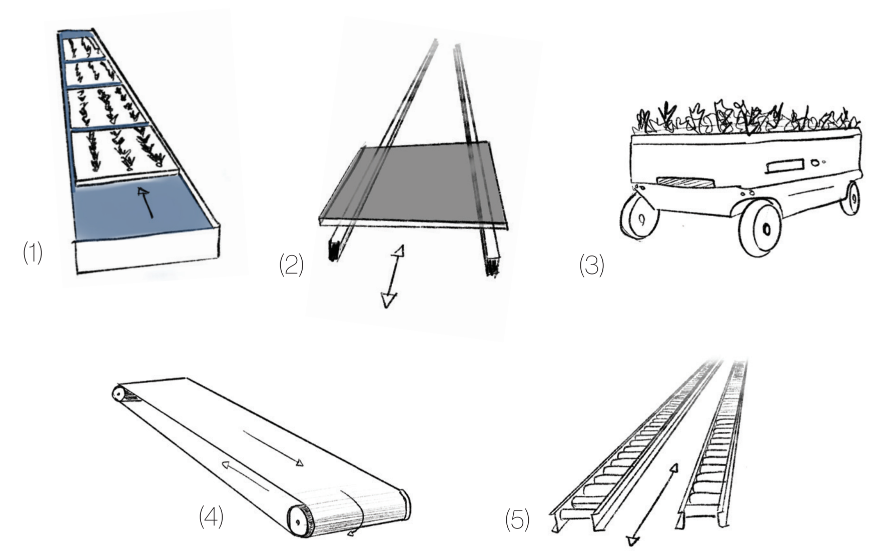
3. Cart Robot: A cart robot can automate the horizontal transport of trays, enhancing efficiency and reducing labor. The robot can be programmed to move trays to specific locations within the farm, ensuring precise placement and retrieval. This is the way Logiqs is currenly operating. (Picture 63)



Picture 63: Bionic Hydroponic's cart robot carrying trays of plants (Bionic)

4. Conveyor Belt: Using a conveyor belt system, trays can be continuously moved across the length of the farming setup.

5. Rolling Tracks: Trays can be moved along rolling tracks, similar to those used in manufacturing lines. This method provides a robust and cheap solution.



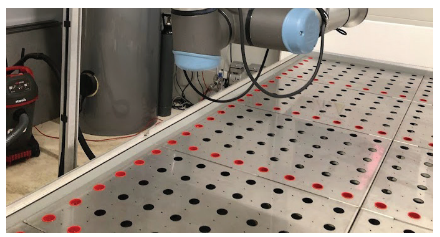
5.1.5- Transplanting the Plants

As plants grow in a vertical farming setup, they often need to be spaced further apart to accommodate their increasing size.

1. Different Patterns of Air and Irrigation Channels: By varying the wavelengths of the tray's corrugated plates, the spacing between the plants can be adjusted. Different patterns in the air and irrigation channels can set the plants further apart as they grow.

2. Changing the Pattern of the Top Sheet: Simply changing the pattern of the top sheet can allow for different spacing configurations. This method is flexible and easy to implement, enabling adjustments without changing the entire tray.

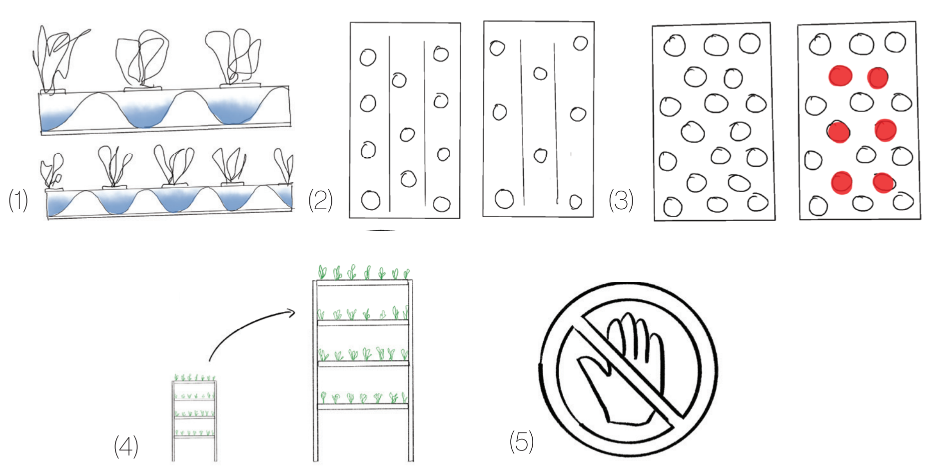
3. Removing Some Plants: Maintain the same tray pattern but remove some of the plants to make space for the others to grow. The open holes must be capped off to prevent light from reaching the water, which could encourage algae growth (Picture 64).



Picture 64: Logiqs' trays with caps to create more space for basil plants to grow

4. Germinating and Growing in Another Farm First: Allow the plants to germinate and grow in a separate facility initially. Once they reach a certain size, transplant them into the trays. This method ensures that only the strongest seedlings are placed into the main farming setup.

5. Not Transplanting: Although less space and energy efficient, you can let the plants grow without transplanting them. This method involves placing the plants far apart from the start to allow enough space for their full growth.



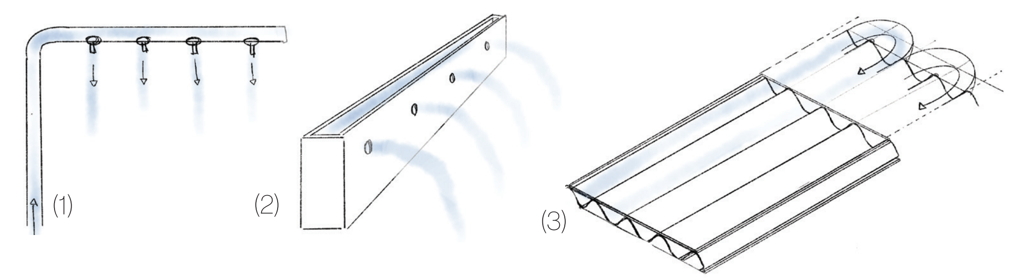
5.1.6- Irrigation

Ensuring an even water flow in each irrigation channel is crucial for the consistent growth of plants in vertical farming

1. Drip Irrigation: This method uses a large pipe connected to a pump to create overpressure, with small perforations that deliver water evenly to each channel.

2. Gravity-Fed Container System : A container placed on top of the system with perforations at a specific height distributes water evenly as it fills up, using gravity for a consistent flow.

3. Connected Channels: Two channels are connected with eachother at the end. The water flows into one channel, turns, and flow back into the connected channel. This reduced the amount of water input and ensures the inlet and the outlet of the water to be at the same side in the farm.



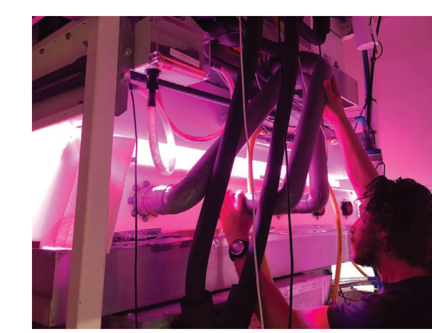
5.1.7- Air Distribution

Ensuring even air distribution designed to connect to the air channels of the trays and provide uniform airflow:

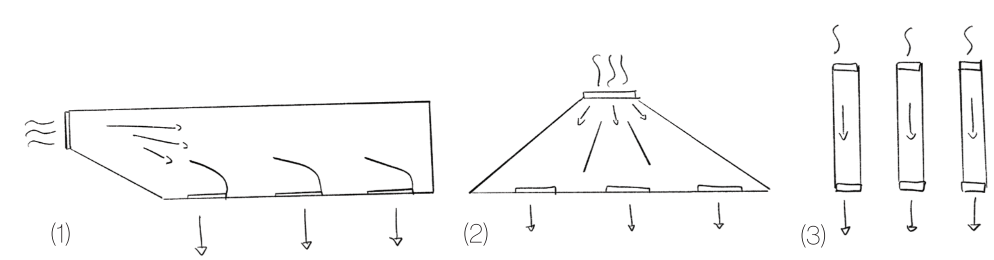
1. Sideways: Air is blown from the side and distributed using flanges to ensure even distribution throughout the trays.

2. Funnel: A centralized funnel, similar to what Logiqs developed for a client, uses distribution flanges to blow air from the center, ensuring uniform airflow across all trays from the middle outwards.

2. Pipes: Each air channel is connected to a separate pipe. (Picture 65)



Picture 65: Idividual pipes on the CEM test at Logiqs



5.1.8- Roof Exhaust

Ensuring uniform air exhaust across the entire top surface of each layer.

1. Corrugated Perforated Roof: This method uses a corrugated, perforated roof that creates channels through which air can be sucked out.

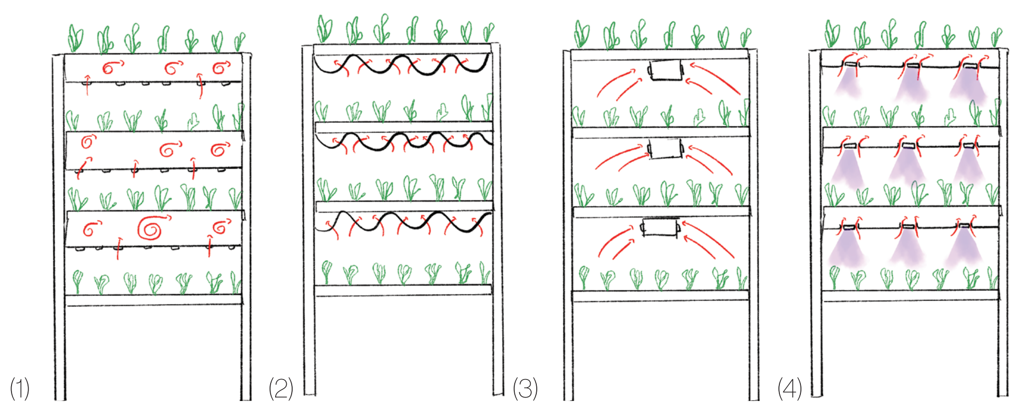
2. Central Perforated Ventilation Pipe: large central pipe with perforated sections serves as the exhaust system for each layer

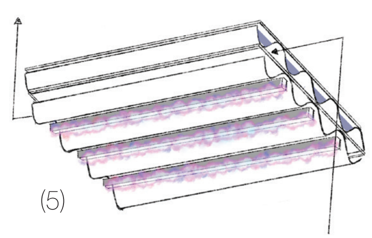
3. Air Room with Distributed Holes: Large air room with distributed holes are used to extract air uniformly across the surface.

4. Exhaust Around LED Lighting: Air is sucked from around the LED lighting, which not only cools the lights but also ensures that hot air is directly removed from the farm. The extracted air is then navigated through channels, enhancing the efficiency of the lighting system while maintaining optimal air conditions (Picture 66).

5. Integrated in tray: Since the trays are stacked, the exhaust system could be integrated in the underside of the ventilation tray, creating a tray that serves as the air inlet and exhaust.

Picture 66: CEM with Pixel lights. The air is being exhausted around the LEDs





5.1.9 - Lighting

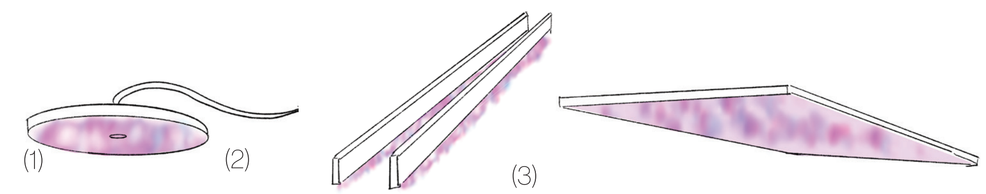
Ensuring even air light distribution.

1. Pixels: Logiqs' own developed lighting solution, Pixels, provides uniform light distribution over an entire surface.

2. Lighting Bars: The industry standard in PFAL involves long LED strips that can be connected in series (Picture 67).

3. Diffused Light Surfaces: This method ensures optimal light distribution by using diffused light surfaces. While it achieves excellent uniformity, it loses on energy efficiency compared to more direct lighting methods. (Picture 68).

Picture 67: Lighting bars in the Urban Crop robotic solution at PLNT Antwerp



Picture 68: Diffused light in the Bever Kar used for germination at PLNT Antwerp

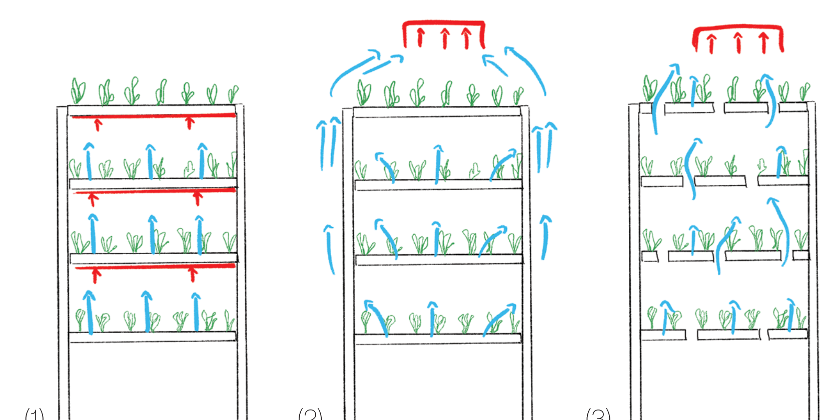
2.3.5 - Exhuast methods

Ensuring effective air exhaust is crucial for maintaining optimal vertical airflow.

1. Exhaust on Every Layer: This method involves installing an exhaust system on every layer of the farm. It ensures that each level has its own dedicated exhaust

2. One Central Exhaust at the Top with Closed Layers : A single central exhaust is placed at the top of the farm, with each layer being closed off. This method creates a chimney effect, where warm air rises naturallyto the sides of the farm, to the top exhaust.

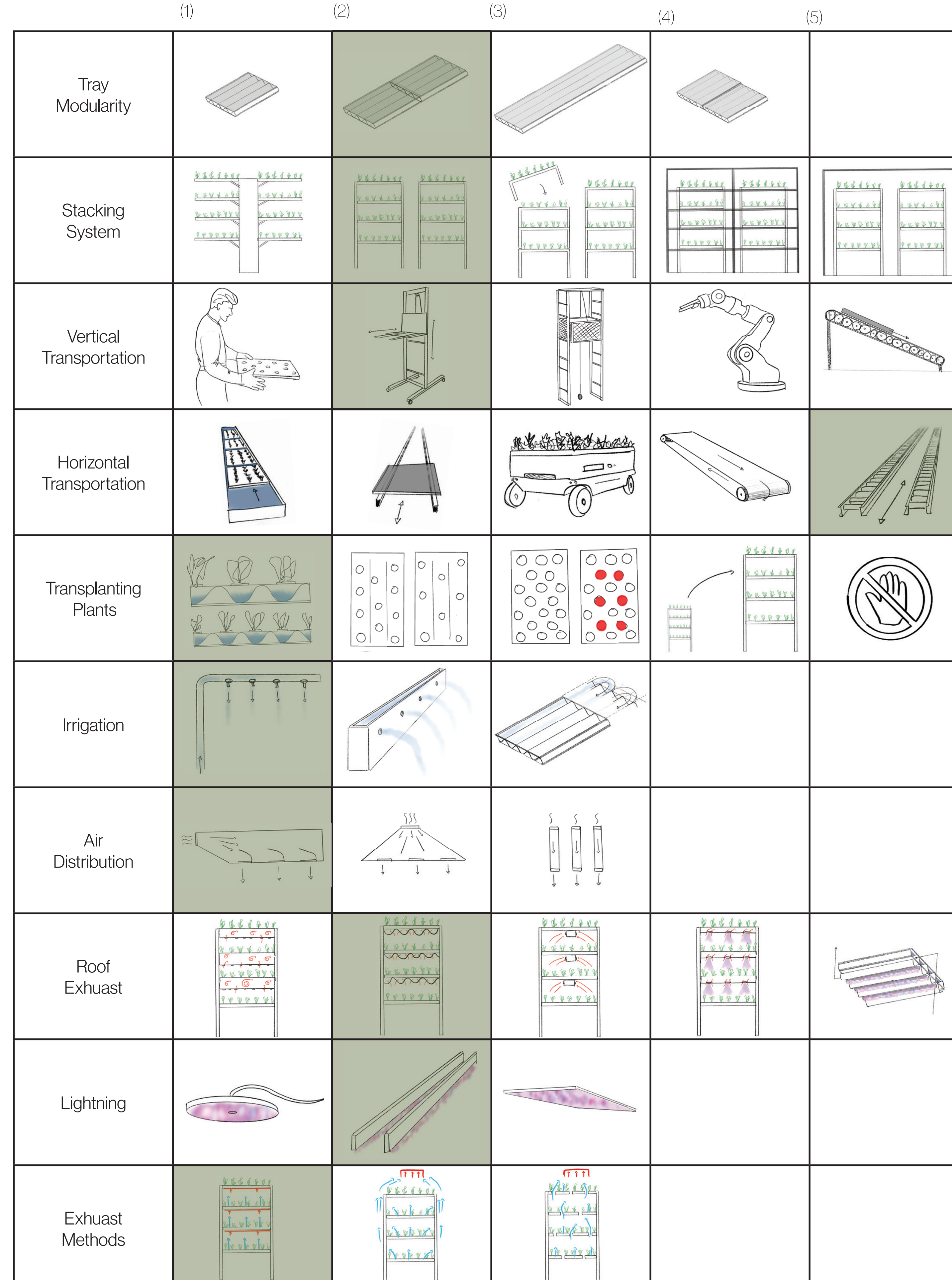
3. Alternating Openings Between Tray Row: By leaving alternating openings between each tray row, air can flow upward through the farm.



5.2- Morphological Matrix

To design an optimal PFAL with the ventilated growing trays, I am using a morphological map, a strategic tool that breaks down complex problems into key parameters of all the subchapters in 5.1 Exploring markets and Ideas. This method systematically lists and evaluates possible solutions for each parameter, creating a comprehensive matrix of options.

By exploring and comparing these combinations, the morphological map helps identify the most effective design configurations, ensuring thorough consideration of all potential solutions.



5.2.1- Chosen Configuration

After evaluating various configurations from the morphological chart, one standout configuration integrates the following elements to optimize the PFAL system:

Tray Modularity: Connectable lengthwise trays, each 3.6 meters long, allow for seamless coverage of the growing area and easy handling (Option 2).

Stacking System: Utilizing a cost-effective racking system to support multiple layers of trays (Option 2).

Vertical Transport: An automated system with a robotic arm lift that moves between rows, collects trays, and places them onto a conveyor belt for efficient handling (Option 2).

Horizontal Transport: Rolling tracks tilted at a 3-degree angle leverage gravity to move trays. This design simplifies collection as trays roll to one end, ideal for Nutrient Film Technique (Option 5).

Transplanting Plants: Different tray sizes with varying patterns and larger wavelengths accommodate plants with bigger root development, providing more water and space (Options 1).

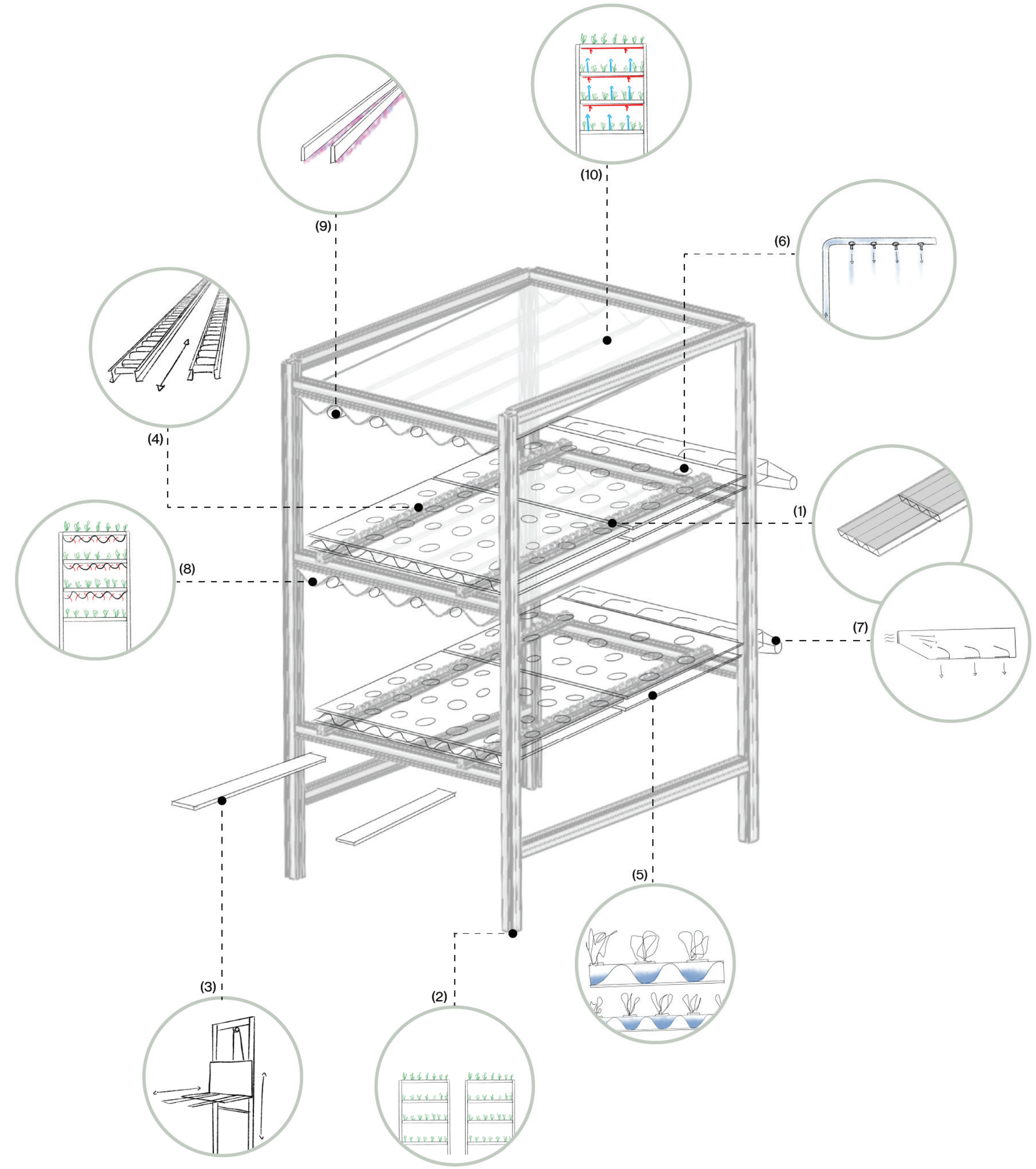
Irrigation: Drip irrigation is chosen for its ease of installation and industry-standard reliability. Due to the 3-degree incline, channels cannot be connected directly (Option 1).

Air Distribution: Sideways air inlet allows for efficient distribution of air to two tray rows with a single air pipe, which can also be used for exhaust, alternating from row to row (Option 1).

Roof Exhaust: Perforated corrugated sheets are used for the roof. These are easy to install and provide excellent control over exhaust across the entire surface (Option 2).

Lighting: Lighting bars (Option 2) are chosen for their ease of installation between corrugated sheets. This positioning places them close to the exhaust, allowing for cooling by passing air.

Exhaust Methods: Installing an exhaust on every layer ensures better control and uniformity of air removal (Option 1).



5.3- Prototype

Creating a prototype for the PFAL concept is a crucial step in transforming theoretical designs into a functional systems. The complexity of integrating various components, such as air distribution, irrigation, lighting, and plant transport, requires hands-on testing to ensure all parts work together. A working prototype allows for real-world testing and validation of the design, uncovering potential issues that might not be apparent in the planning stages. By constructing a prototype farm, I can observe and measure the interactions between different elements, refine the design based on practical insights, and ultimately ensure a robust and efficient vertical farming system. This approach minimizes the risk of overlooking critical aspects and accelerates the development of a fully operational PFAL.

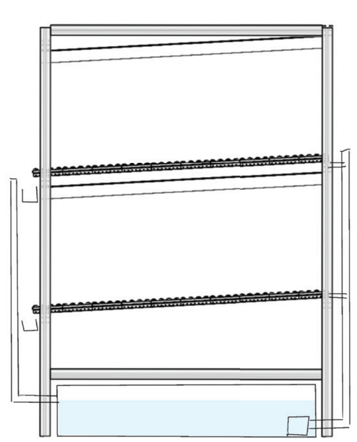
5.3.1 - Ideation

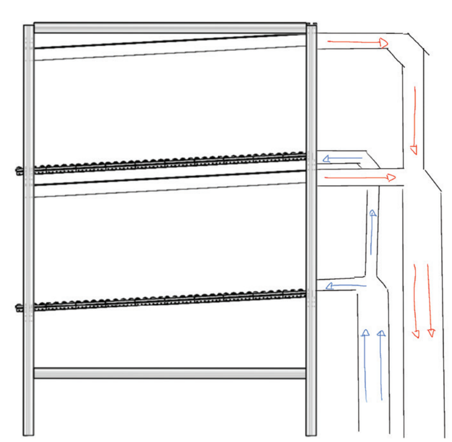
I decided to create a mini farm prototype. Each layer of the prototype will feature a rolling track, capable of holding two layers, for a total of four trays. This setup can accommodate 216 basil plants.

The prototype will include exhaust pipes to test air distribution and ventilation efficiency. Instead of using bar lights, I will utilize Logiqs' Pixel Lighting solution for more precise light distribution. The frame of the prototype will be constructed using aluminum profiles, which allows for modular building and easy assembly and disassembly.

Each layer will have its own sideways ventilation distribution for both air inlet and exhaust, ensuring optimal airflow. The irrigation system will be installed by placing a container underneath the system, which will pump water in a cycle, providing consistent hydration to the plants. This mini farm prototype will help in testing and refining the design, ensuring all components work seamlessly together and identifying any potential issues early in the development process.

Picture 69, 70: Prototype Idea irrigation, Prototype Idea Ventialtion





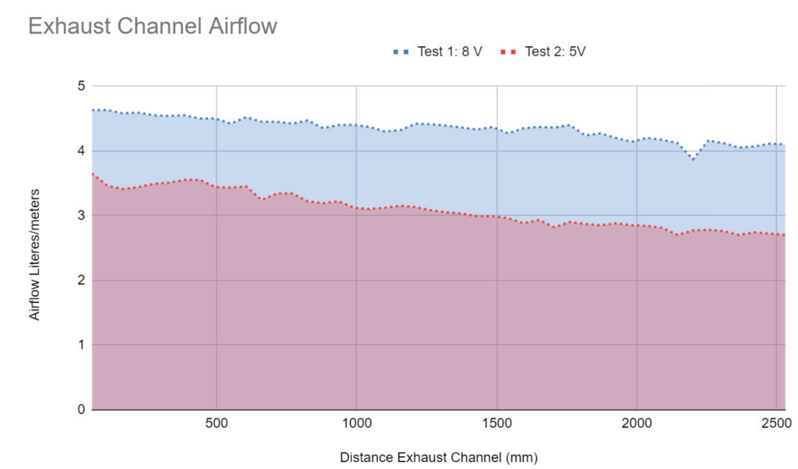
5.3.2 - Exhaust Roof

To develop the optimal hole pattern for air exhaust, it was essential to conduct a specific test due to the significant differences in behavior between air exhaust and air inlet. Additionally, the unique shape of the channel required a thorough examination of airflow characteristics.

I conducted this test on a 2500 mm length of the channel, capping off the end to observe the pressure and flow dynamics. Based on previous tests, I selected a hole pattern with 8mm diameter holes spaced 55mm apart, with one hole on each side of the channel. The direction of the ventilator was reversed to function as an exhaust rather than an inlet, and two tests were performed: one with a higher airspeed input and one with a lower airspeed input.

Test Results

The test results indicated a significant drop in uniformity of the airflow. Specifically, the farther from the ventilator, the less effective the exhaust became. Over the entire 2500 mm length, there was a pressure drop of 20.81%. By breaking the pipe into sections of 500mm, it was observed that every 500mm experienced an approximate pressure drop of 5.21%.



Picture 71: One 2.5 meter test for exhaust on the corrugated roof measurement

Adjustments for Improved Uniformity

To counter this drop in pressure and improve uniformity, I decided to adjust the hole pattern. By creating a linear gradient in the hole spacing, I aimed to balance the pressure distribution. This involved increasing the number of holes towards the end of the pipe. Specifically, every 500mm section now includes an additional half hole to maintain more consistent airflow and pressure across the length of the channel.

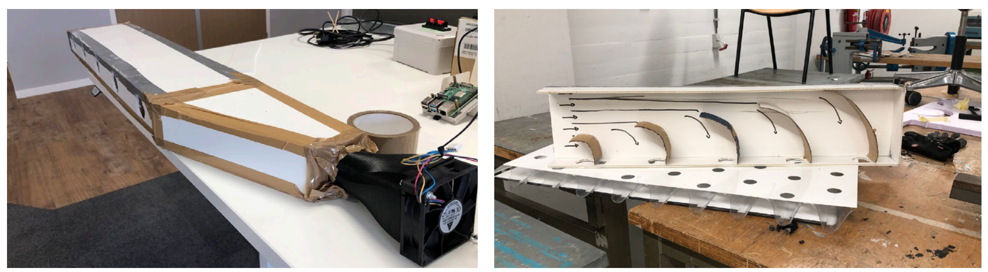
These adjustments will help ensure a more uniform air exhaust, enhancing the overall efficiency and effectiveness of the PFAL system. Further tests will be conducted to refine this pattern and verify its performance in different operational conditions.

5.3.3- Exhaust pipe

With the ventilation channels and hole patterns defined, the next step was to design the sideways air distribution tube. I decided to create a casing with five holes that would fit perfectly onto the farm's structure, incorporating round flanges within the case to ensure effective exhaust distribution.

Initial Prototype

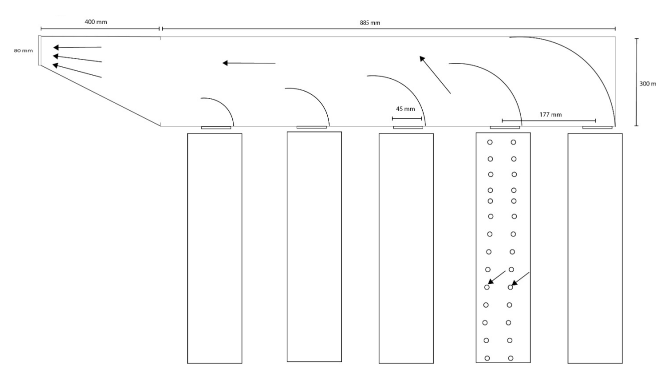
I began by constructing a cardboard prototype to estimate the air distribution. However, the initial test revealed that the air distribution was not satisfactory. Without precise calculations for the exact height and radius of the flanges, achieving the desired airflow was challenging.



Picture 72, 73: Exhaust pipe prototype test with ventilator, Drawing on air movement in the pipe for inlet pipe prototype

Computational Fluid Dynamics (CFD) Simulations

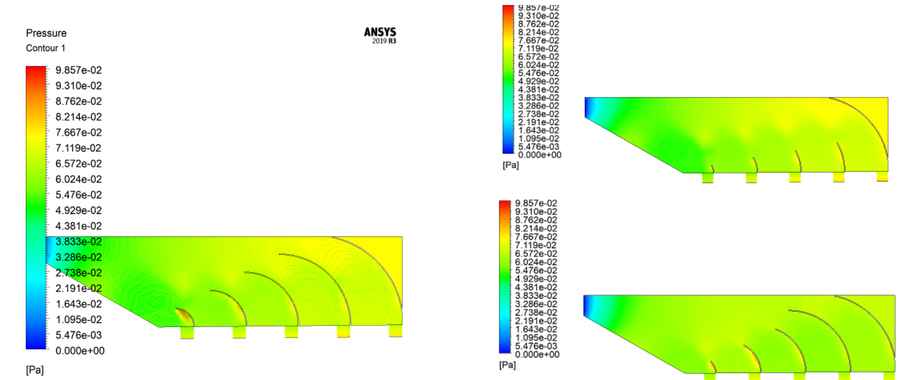
To refine the design, I turned to Computational Fluid Dynamics (CFD) to iterate on different configurations:



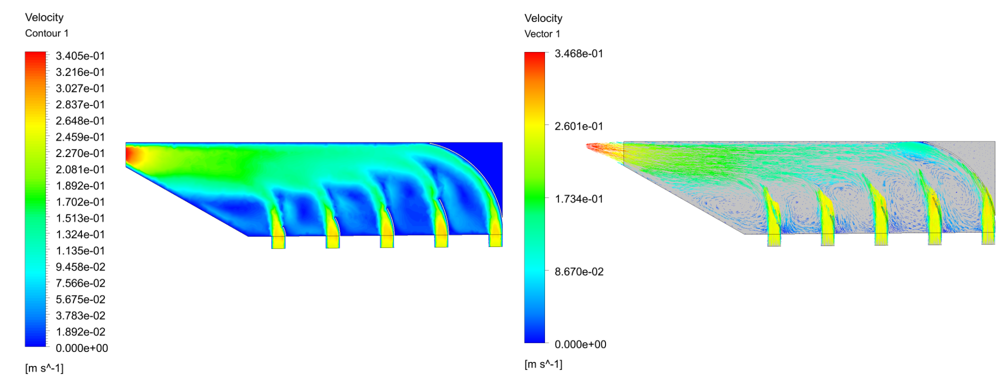
Picture 74: Schematic representation of exhaust pipe

By the third iteration, the CFD simulations indicated satisfactory air distribution. This design provided a balanced airflow, effectively addressing the initial issues observed in the cardboard prototype.

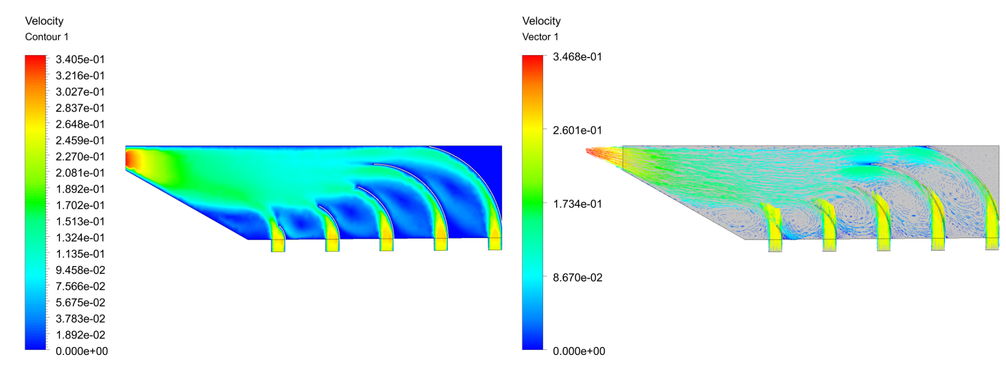
Satisfied with the results from the CFD analysis, I decided to proceed with this final design for the sideways air distribution tube.



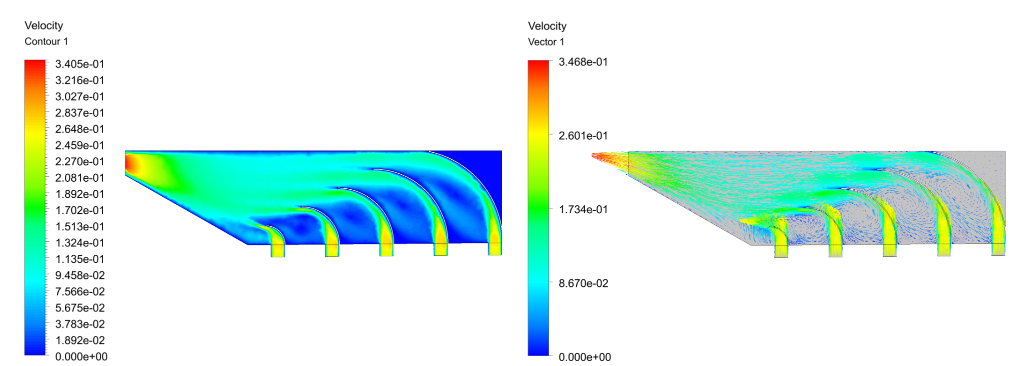
Picture 75: Pressure Exhaust pipe tree configuratuions of flanges



Picture 76, 77: Air velocity of model 1, velocity vectors model 1



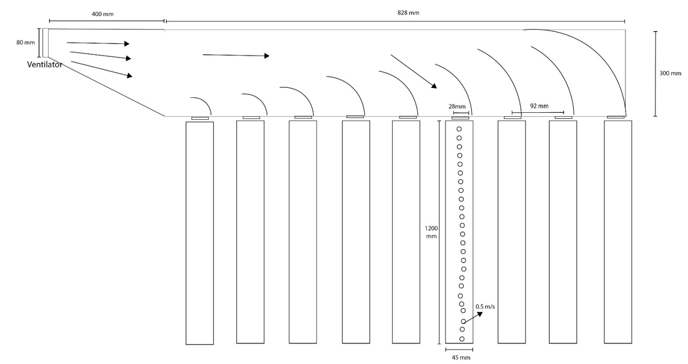
Picture 78, 79: Air velocity of model 2, velocity vectors model 2



Picture 80, 81: Air velocity of model 3, velocity vectors model 3

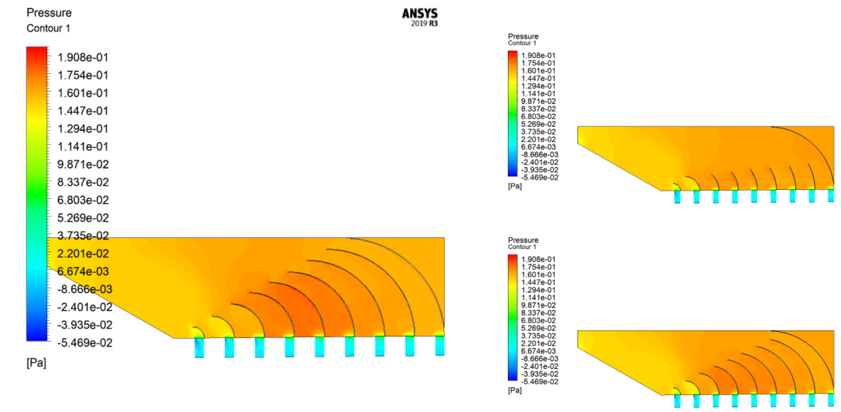
5.3.4- Inlet pipe

The same methodology ad the design of the outlet pipe was applied for the air inlet. The case of the tube has the same dimentions. Only the flanges within the case differ.

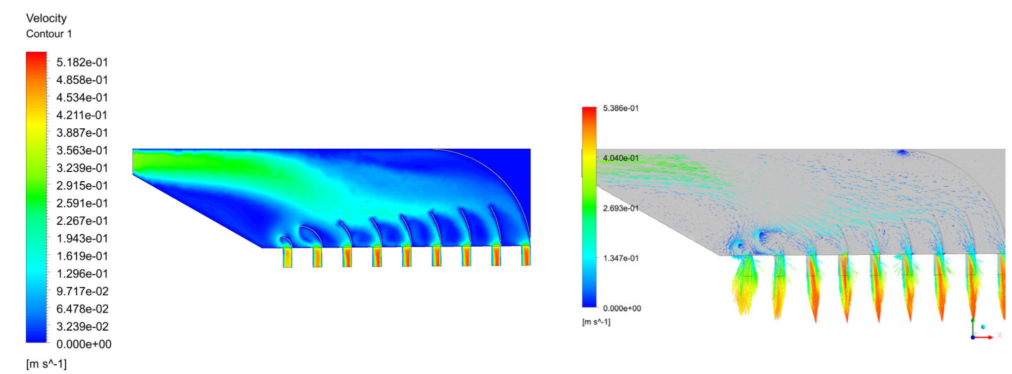


Picture 82: Schematic representation of inlet pipe

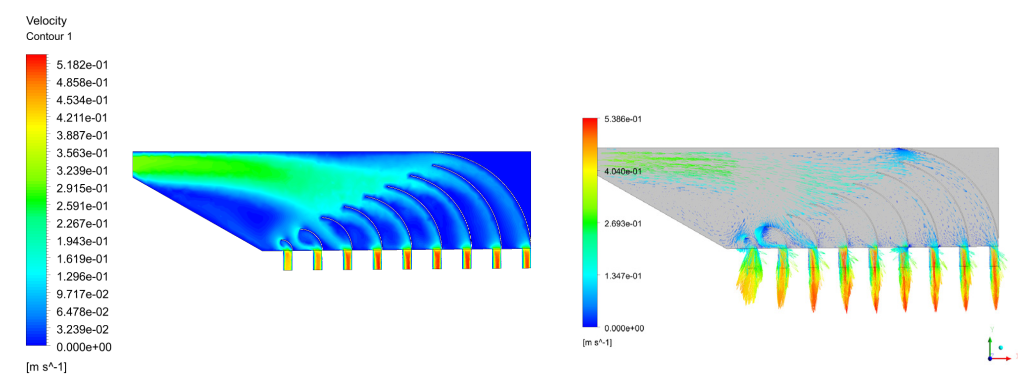
Again, tree iterations were done on the flanges and I decided to go troug with the last iteration, having the best distributed airflow.



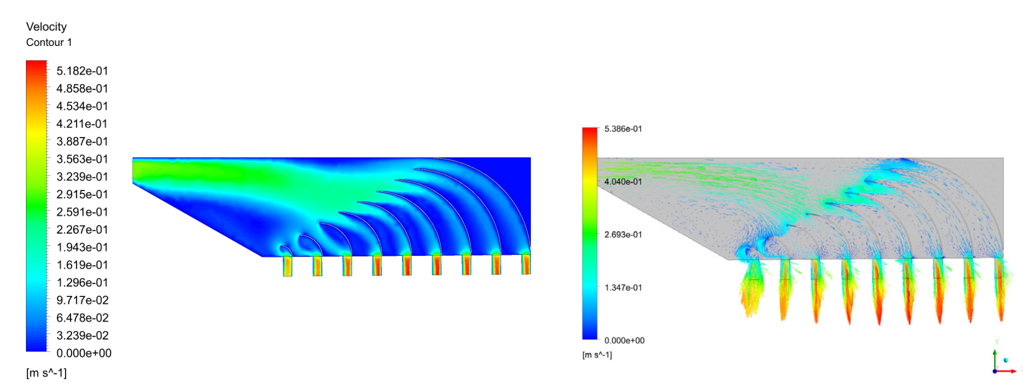
Picture 83: Pressure Exhaust pipe tree configuratuions of flanges



Picture 84, 85: Air velocity of model 1, velocity vectors model 1



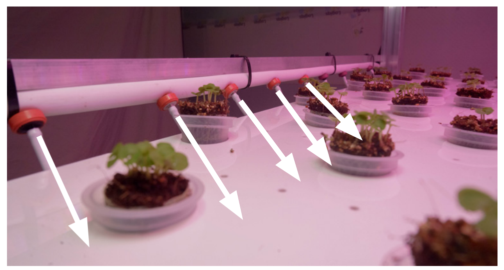
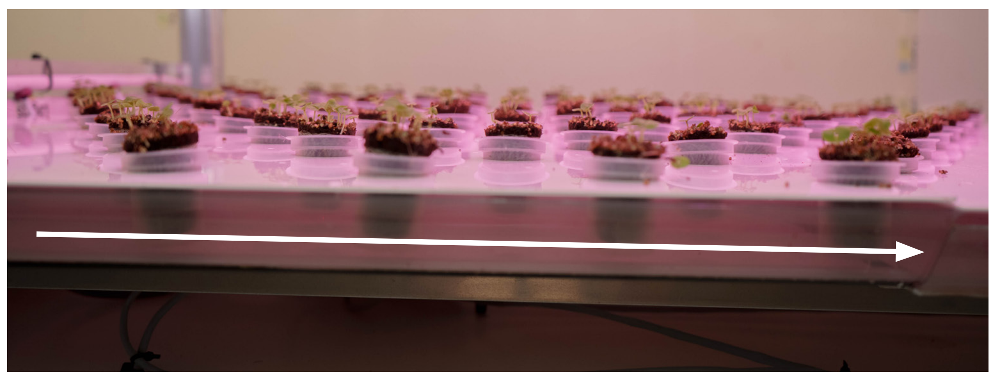
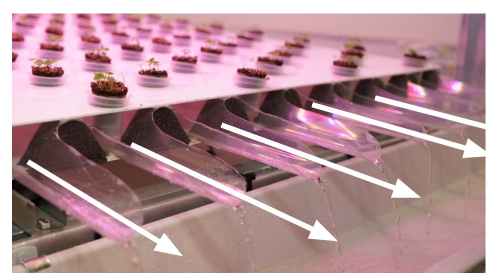
Picture 86 ,87: Air velocity of model 2, velocity vectors model 2



Picture 88, 89: Air velocity of model 3, velocity vectors model 3

5.3.5- Irrigation

The irrigation system was tested by evaluating different irrigation drippers under a pressure of 1.5 bar applied to the pipe where the drippers are mounted. The tests included drippers with flow rates of 3 liters/hour, 6 liters/hour, and 10 liters/hour. Based on the results, I decided to use drippers with a flow rate of 6 liters/hour, as this configuration perfectly filled each channel with a thin film, ensuring adequate nutrient delivery to the plant roots.

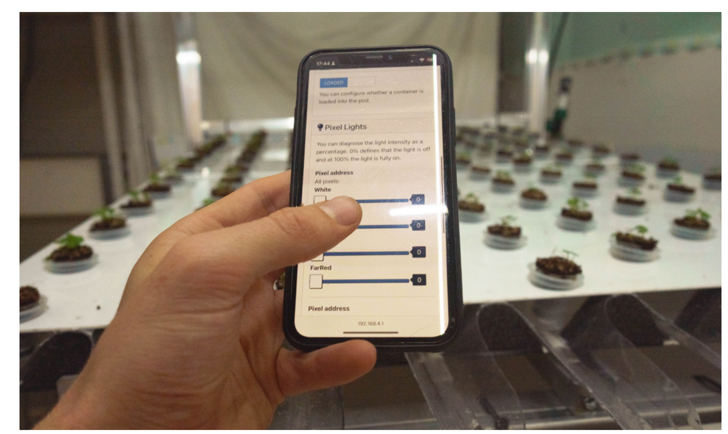




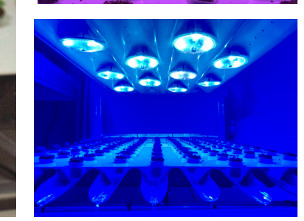
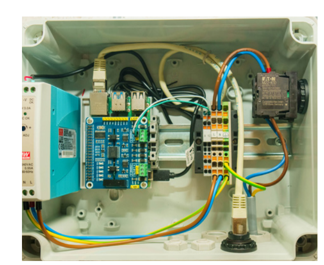
Picture 90, 91, 92: Water inlet with irrigation drippers, Water flowing trough the channels, Water exiting at the end of the growing tray row into the gutter

5.3.6- Lightning

In the prototype of the PFAL, the LED lighting system is essential for plant growth. Ideally bar lights are installed between corrugated roof panels to ensure proper cooling. I used Logiqs Pixel lighting solutions, positioned just above the exhaust to enhance cooling and efficiency, which works as well.

These lights are connected to a Raspberry Pi with its own Wi-Fi network, allowing any phone to connect and adjust each layer or light individually through an interface. This setup ensures optimal light conditions for the plants, enhancing their growth and development.

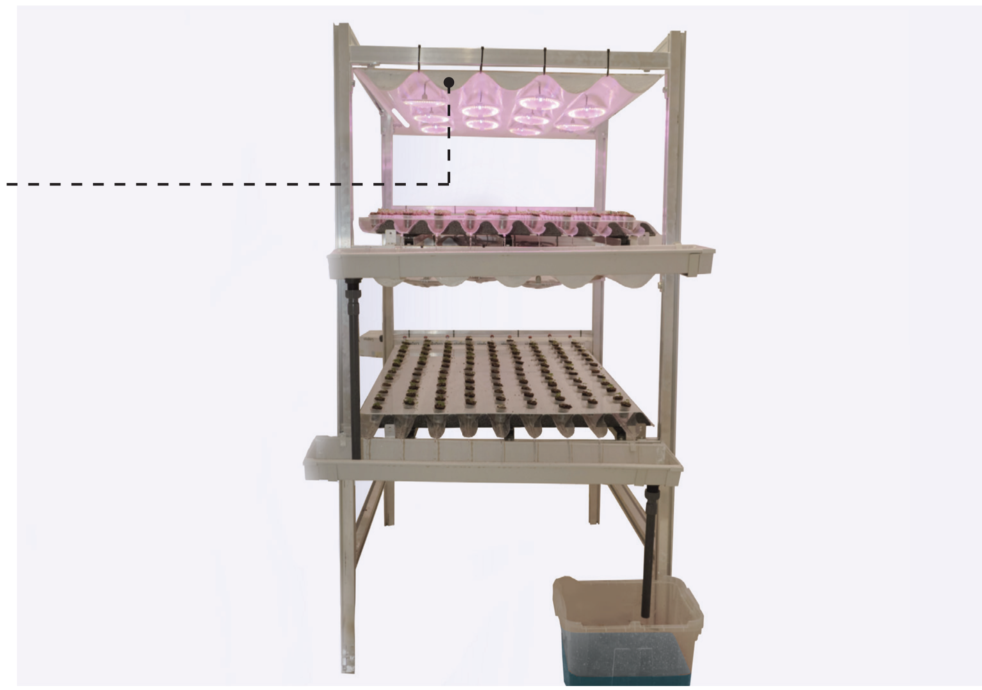



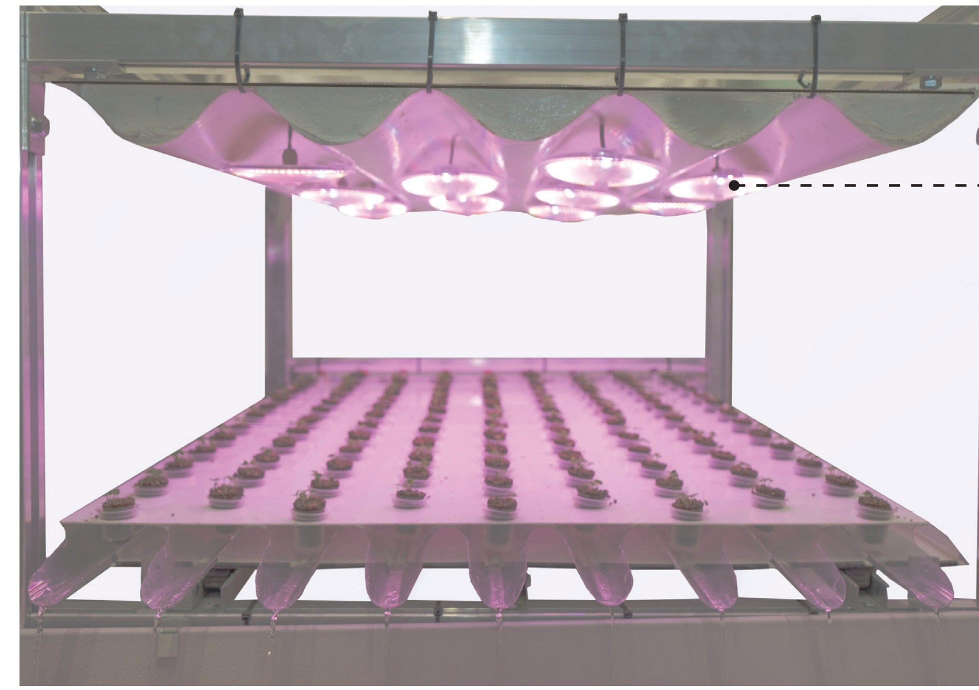



Picture 93, 94, 95, 96, 97: Lamps attached to roof, Interface for control Pixel lights, Purple Pixels, Bleu Pixels, Rasberry Pi controlling the Pixels.

5.3.7- Final Prototype

All the parts—the exhaust roof, exhaust pipe, inlet pipe, irrigation system, and lighting—come together in a final prototype that holds four trays. The inlet and exhaust pipes are equipped with computer ventilators, eliminating the need for external pipes. This integrated system ensures efficient air circulation, proper irrigation, and optimal lighting conditions, creating an ideal environment for plant growth.





CHAPTER SIX

RESULTS

This chapter will delve into the results of the design process, presenting my final design and evaluating how it functions and performs as a PFAL system.

06.

6.1- Introduction

In this chapter, I will present the results of the PFAL system analysis across four different levels of detail, starting from the smallest scale and progressing to the largest. This structured approach ensures a comprehensive understanding of the system's performance and integration.

The first level is the micro level, which focuses on the processes occurring within a single plant. This includes detailed examination of air movement, gas exchange, and photosynthesis at the leaf level.

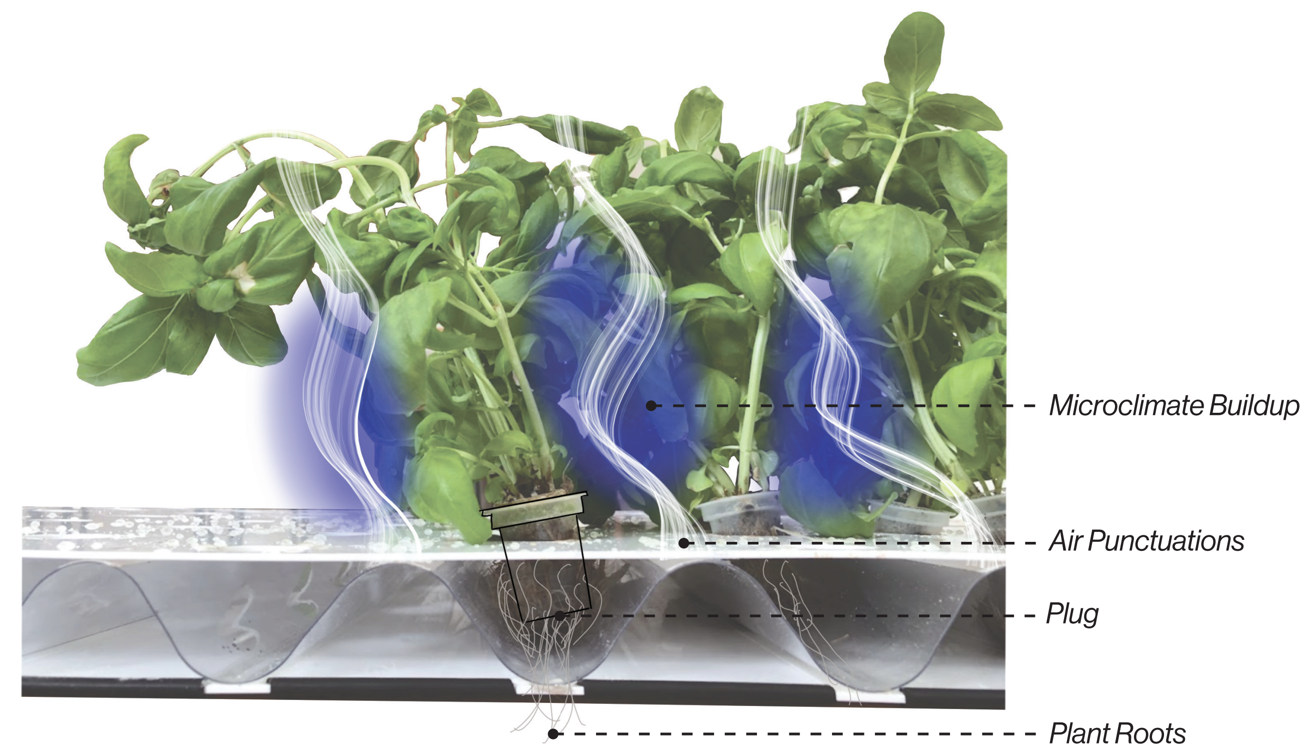
The second level is the meso level, occurring on the scale of the growing tray. At this level, the interactions between plants and the immediate environment within the tray are analyzed, including how air flows vertically around the plants and how irrigation is distributed.

The third level is the macro level, which involves to the scale of the prototype. This involves the same principles and technologies as a full farm setup, such as irrigation and air distribution, but on a smaller scale. It allows for testing and validation of the system components in a controlled environment.

Finally, the fourth level is the meta level, which examines the farm operating at full scale. This includes the overall integration of all systems and the interaction between multiple farms, exploring the scalability, efficiency, and potential for resource sharing in large-scale operations.

6.2- Micro Level

The plants are grown in coco fiber within a plastic plug that can be inserted into a plate. Each plant is placed at an optimal distance from one another to ensure maximum yield while still receiving sufficient light. Given the close proximity of the plants, a microclimate and humidity build up between them. Due to the minimal air punctuations, air flows vertically into the plant canopy, effectively blowing the accumulated humidity out of the plant canopy. This process creates a climate layer with the ideal temperature around the entire plant, promoting healthy growth and preventing moisture-related issues.

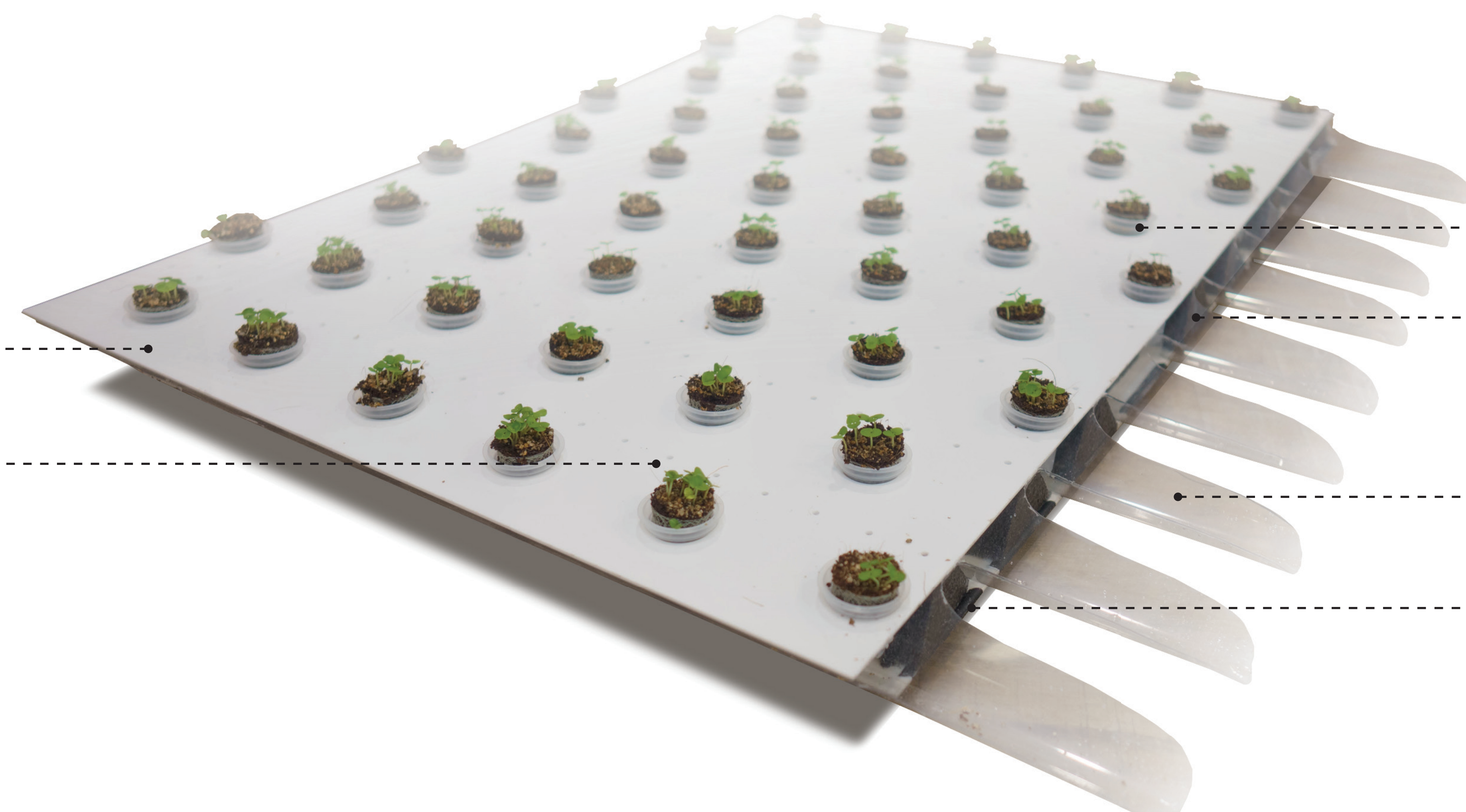


6.3- Meso Level

The plants are all placed into the growing tray, which is constructed from a PVC corrugated sheet. White PVC plates have been glued on each side of the corrugated sheet to enhance stability and durability. Holes are then laser-cut automatically into the top layer, with a protective fork layer inserted into the channels of the growing tray to shield the underlying layer. This automated process allows for the implementation of different air patterns to optimize air flow.

The even white surface of the trays reflects light back onto the plants, ensuring that they receive ample illumination from all angles. One side of the corrugated sheet features male parts that can be easily connected to another growing tray, ensuring seamless water flow between trays.

The trays are designed for easy cleaning; brushes can be shoved into the channels to scrub the interior, and they can be steamed for complete sterilization, ensuring a hygienic environment for the plants.

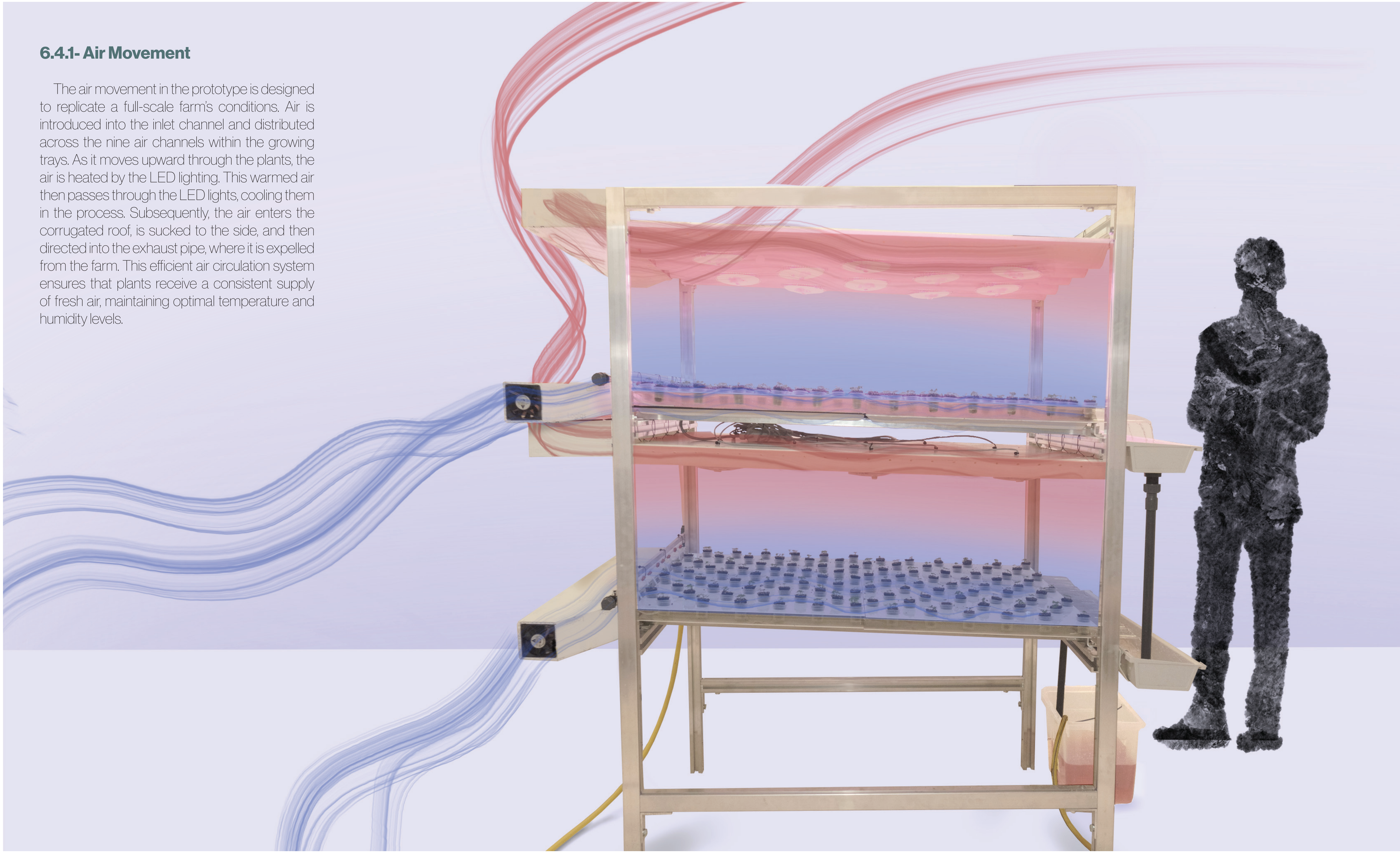


6.4- Macro Level

The macro level involves all the aspects of the farm and their functionalities as represented in the prototype. Three important factors of this farm are air distribution, the irrigation system, and the handling of the farm, including loading and unloading processes.

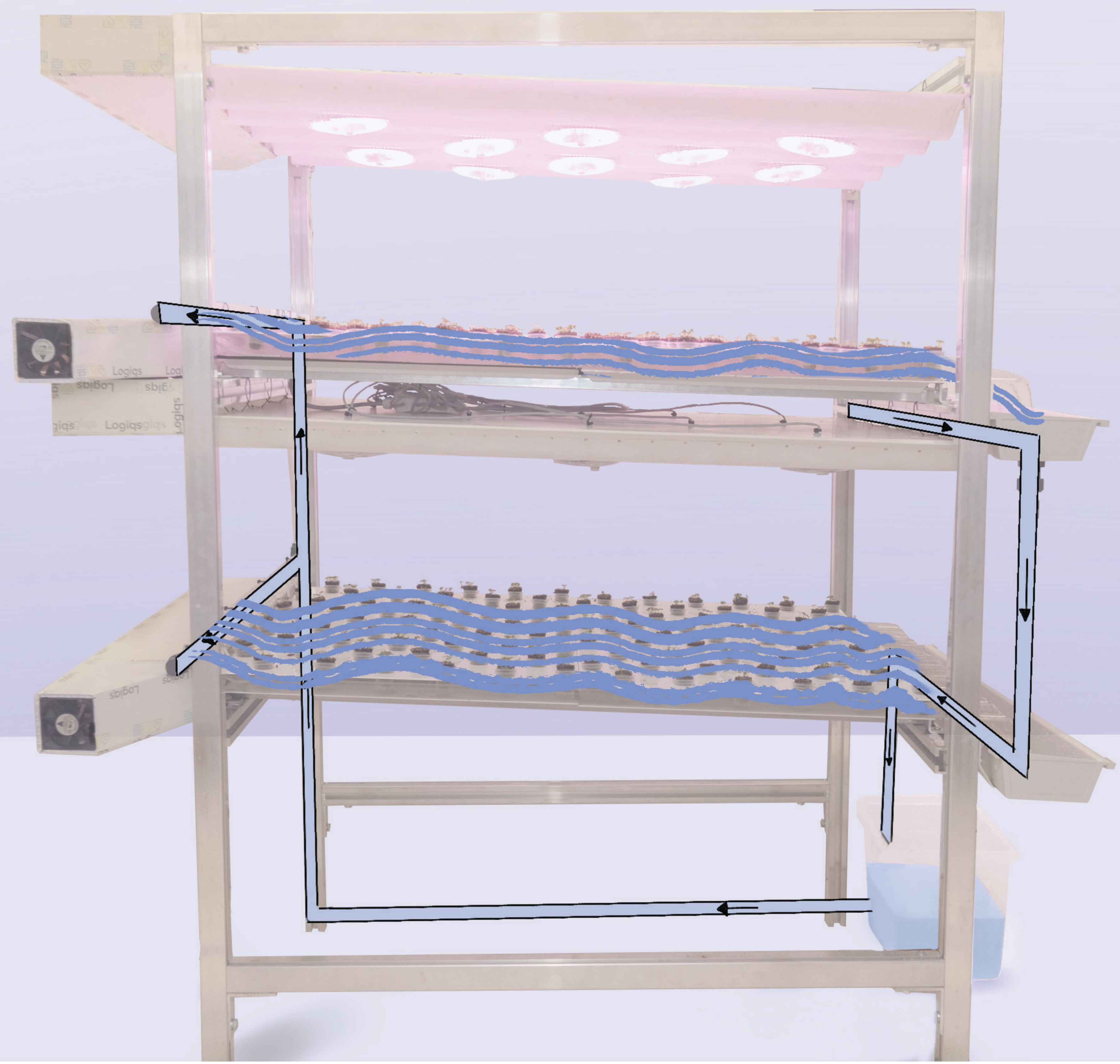
6.4.1- Air Movement

The air movement in the prototype is designed to replicate a full-scale farm's conditions. Air is introduced into the inlet channel and distributed across the nine air channels within the growing trays. As it moves upward through the plants, the air is heated by the LED lighting. This warmed air then passes through the LED lights, cooling them in the process. Subsequently, the air enters the corrugated roof, is sucked to the side, and then directed into the exhaust pipe, where it is expelled from the farm. This efficient air circulation system ensures that plants receive a consistent supply of fresh air, maintaining optimal temperature and humidity levels.



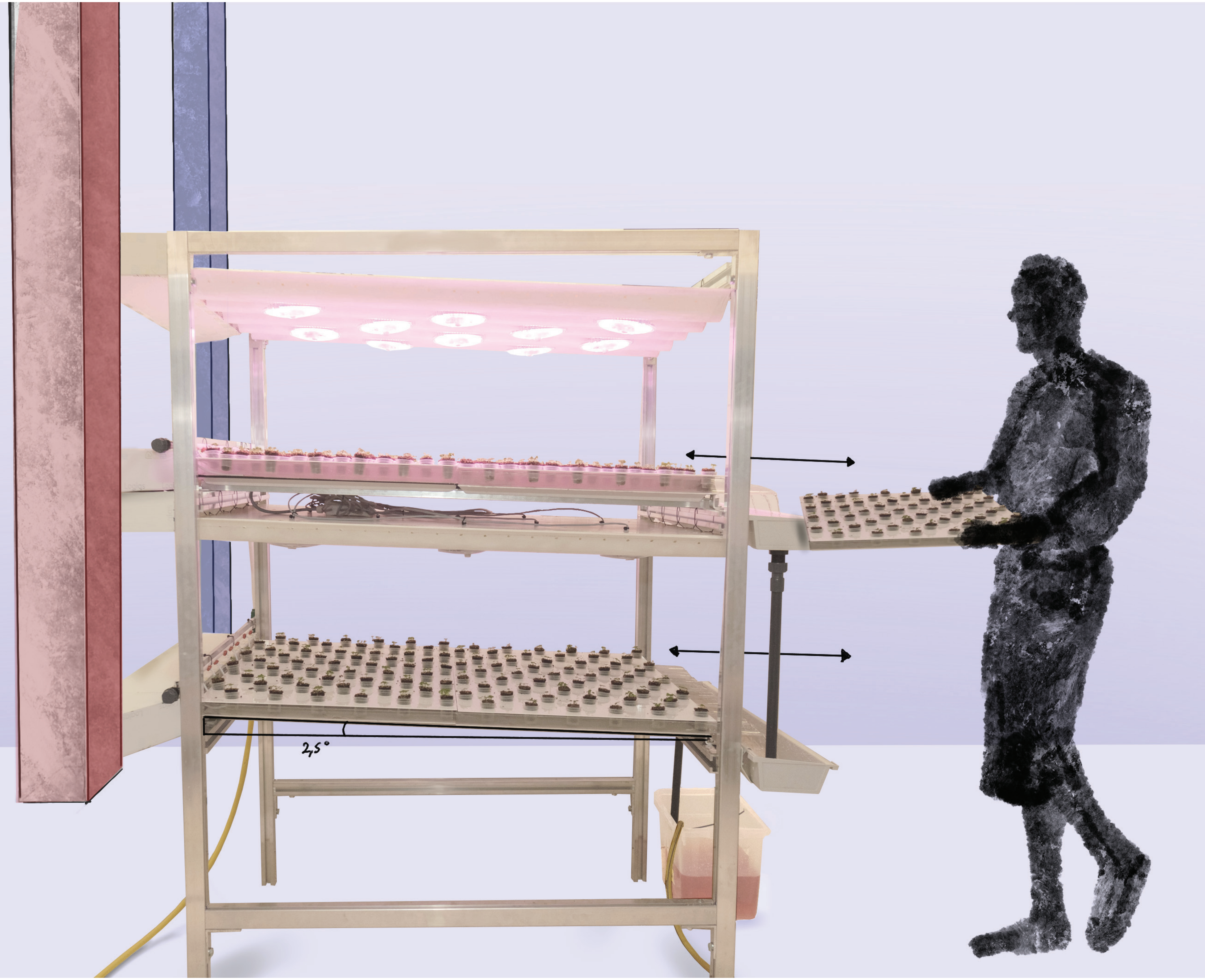
6.4.2- Irrigation

The farm includes a water container where the water is treated to adjust pH levels and add necessary nutrients. A pump then distributes this nutrient-rich water into the various layers of the farm via PVC pipes. These pipes are perforated with drip irrigation parts connected to small tubes, which distribute water into the nine channels of each growing tray. The water flows down to the other side of the farm, where it is collected in a gutter and returned to the container for recirculation. This closed-loop system ensures efficient water usage and consistent nutrient delivery to the plants.



6.4.3- Handeling the Farm

The handling of the farm is streamlined by placing the growing trays on rolling tracks set at a 3-degree angle. Since all water input, air blow, and exhaust systems are located on the outer edge of the farm, people or robots only need access to one side. When irrigation and air systems are turned off, the farm can be loaded from one side by sliding a new growing tray into place, pushing the previous tray forward. During unloading, the entire row of trays rolls automatically towards the operator. To prevent all trays from rolling down at once, stops are installed to control the movement of the trays. Once a full row is loaded, irrigation and ventilation can be reactivated, and the row can remain in place until it is ready for harvest. This design ensures efficient and ergonomic management of the farm.

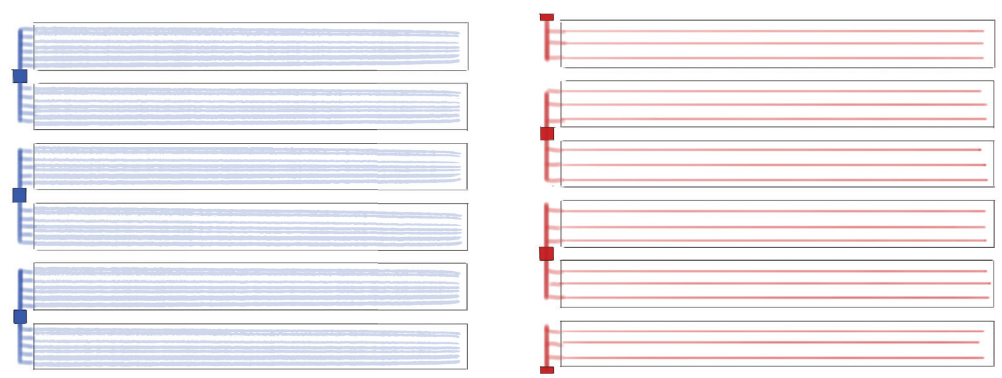


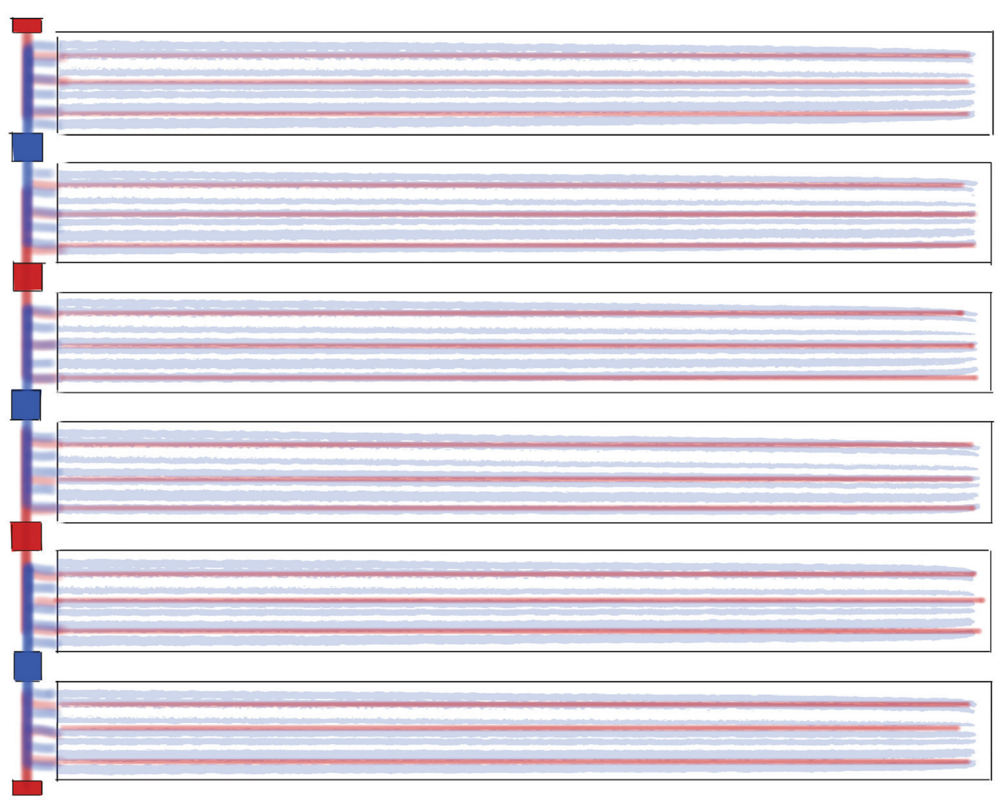
6.5- Meta Level

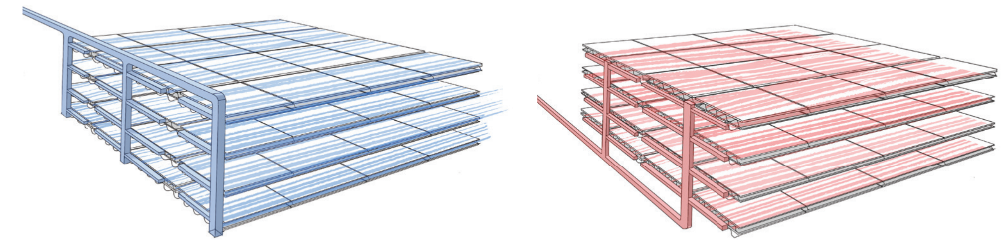
The meta level explores how a full-scale farm would operate and how air would be distributed when multiple rows are placed next to each other, ensuring a modular and efficient design of the farm.

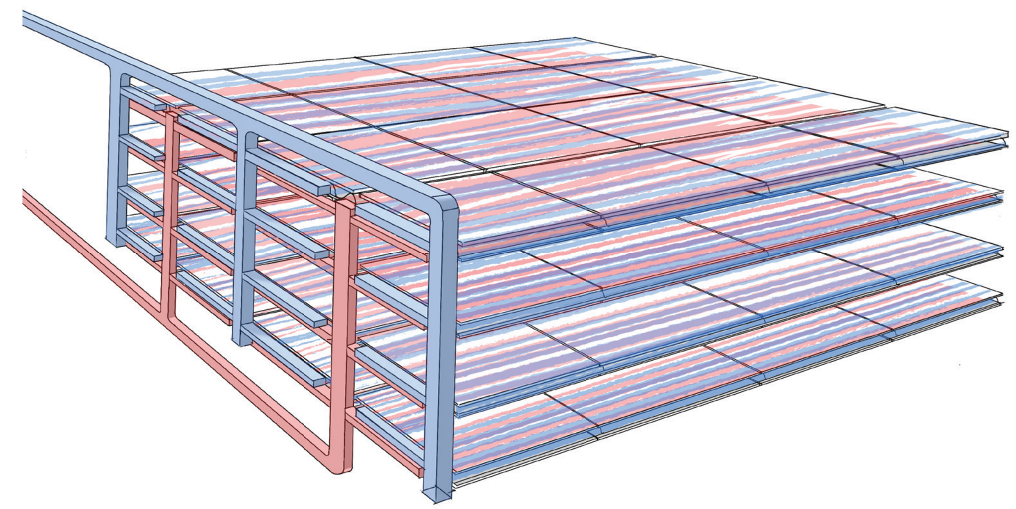
6.5.1 - Air Movement

In the top view, the inlet (red) and exhaust (blue) pipes are alternated, each splitting into two and covering the rows on both sides of the pipe. This alternating pattern ensures balanced air distribution across the entire farm, maintaining optimal growing conditions for all plants.



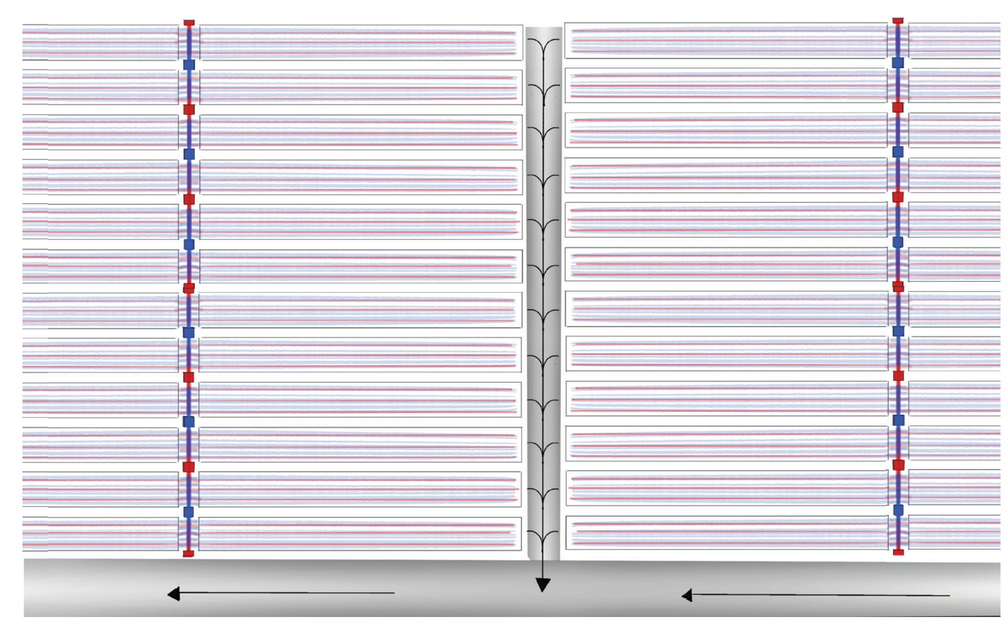






6.5.2- Tray Movement

When viewing multiple row clusters next to each other, the farm can be engineered so that all ventilation pipes run in rows, covering both sides. This design creates minimal space requirements for moving the trays, whether by humans or robots. The efficient layout allows for seamless tray movement, ensuring easy access for loading, unloading, and maintenance operations.



CHAPTER SEVEN

DISCUSSION

The discussion phase involves analyzing and interpreting the outcomes of the design process and validation. It offers a chance to reflect on the results, evaluate the project's strengths and weaknesses. Considering the implications of the findings for future design recommendations and reflect on the design process.

07.

7.1- Design Benefits

7.1.1- Growing Tray

The proposed growing tray offers unique features that make it stand out in the market. It helps create a consistent climate around the farm by providing vertical air supply within the plant canopy. This feature is new and not yet available in other designs, promising better crop growth and health. The trays are lightweight and easy to handle, both by humans and machines. Their corrugated structure makes them strong and durable, preventing warping under the weight of plants and water.

The trays can be mass-produced using automated techniques, making them affordable for large-scale farms. The design is flexible, allowing for different sizes and configurations, such as taller or more compact trays to suit various farming needs. This adaptability ensures that the trays can be customized for different types of crops and environments, increasing their usefulness.

Another significant benefit is that the tray design fits perfectly within the CEM used by Logiqs. This compatibility makes it easy to implement without major modifications, optimizing climate control within the CEM as well. It would also mean that only the grpwing trays would be movinf in and out the CEM, leaving the big aluminium frame under the CEM, therefore, being able to pack more CEMs next to eachother.

7.1.2- Farm System

The farm design maximizes space efficiency by placing ventilation and irrigation systems on one side, leaving the other side free for loading and unloading trays. This layout optimizes space and simplifies operations, reducing labor and time. The corrugated roofs are easy to install since they can be pre-made and pre-drilled, eliminating the need for complex tube connections.

The roofs also have gaps for installing LED bar lighting, which is cooled by the exhaust system, saving energy and extending the LEDs' lifespan. The 2.5 to 3-degree angle of the trays ensures a continuous flow of nutrients to the plant roots, crucial for healthy growth. This angle also helps with the automated loading and unloading of trays, making maintenance easier by allowing complete tray removal, preventing organic matter buildup.

Finally, this design is super lightweight and efficient, using minimal materials. Many functionalities are integrated into the growing tray, making it easy to clean, install, and maintain. This also enhances cost efficiency.

7.2- Design Limitations

7.2.1- Growing Tray

Despite its many benefits, the tray design has some limitations. The trays can sometimes warp at the edges, creating gaps that let air escape, affecting the uniformity of air distribution. Fixing this issue is essential for maintaining the efficiency of the air supply system.

Additionally, while the trays can be designed in various configurations, different tray designs cannot be mixed within the same row. This means that if a different tray design is needed, the entire row must be replaced, which can be costly and reduce flexibility.

If the trays are used within the CEM, rolling tracks would ideally be needed for tray movement. This also means the CEM would need an incline to ensure the trays roll in and out correctly and provides the right irrigation.

Finally, the air inlet is not yet fully designed, especially the connection of the air pipe with the growing trays needs to be developped. This is a key component to the farm's design which is essential in the operation of it.

7.2.2 - Farm System

Setting up a new farm can be challenging due to the need for it to be cost-effective and the time required for the industry to adapt. Existing machinery and robotics are designed for current farm layouts, so a new design would require big changes in equipment and infrastructure. This can be a major barrier to adoption.

7.3- Design Recommendations

The following are recommenditions to look into if the project is to be continued.

7.3.1 - Growing Tray

Optimize Air Connections

Ensure all air connections are sealed properly to prevent leakage, maintaining uniform air distribution. Using precision manufacturing techniques like extrusion or injection molding to create tighter seals. Adding rubber paddings to the sides for better connections

Material Improvements

Explore alternative materials or design modifications to reduce tray warping. ensuring a better connection.

Enhanced Prototyping and Testing

Allocate more time for extended testing periods, allowing multiple growing cycles to be evaluated. This will provide a more comprehensive understanding of tray performance over time. And the plants behaviour.

Integration with Sensors

Incorporate sensors for real-time monitoring of temperature, humidity, and airflow. This will help in maintaining optimal growing conditions and improving crop health. Look into potentially adding the sensors in the growing trays.

7.3.2- Farm System

Large-Scale Testing

Conduct large-scale tests to monitor climate behavior throughout the farm using sensors within the farm to gather data on temperature, humidity, and airflow. As such, we can measure how flowing air from every layer affects the overall farm's climate.

Controlled Sections

Divide the farm into sections to enable better control over the environment in each part, allowing for more precise climate management. So finding a way to separate every layer and every row from eachother with isolating panels for example

Modular Design Enhancements

Improving the modularity of the design to make assembly and disassembly easier. This can involve using quick-connect systems and standardized components that simplify setup and maintenance.

7.4- Design Process

2.4.1 - Growing Tray

The design process for the tray used the double diamond approach, involving multiple phases of exploring ideas and refining them. This method was effective in generating a wide range of ideas and then focusing on the best solutions. Rapid prototyping and testing of air principles with tubes and ventilators were crucial in understanding air behavior and applying it effectively in the design. These prototypes allowed for real-world testing and improvements, ensuring the final design was both functional and efficient.

Time constraints limited the ability to test multiple prototypes and run full growing cycles, but the iterative approach still provided valuable insights. Future projects could benefit from more time for extended testing periods, allowing for multiple growing cycles to be evaluated and further refinements made.

2.4.2 - Farm System

Using a morphological matrix was key in mapping the industry and generating innovative solutions. This structured approach helped manage the complexity of integrating various technologies. Building a working prototype allowed for practical application and testing of ideas, providing valuable insights into how the system operates in real-world conditions.

The prototype stage was particularly beneficial in identifying potential issues and making adjustments before full-scale implementation. However, further testing with real users would have been helpful.

By addressing these aspects, the project aims to advance the design and implementation of vertical farming systems, contributing to the development of sustainable urban agriculture solutions.

Picture 98: Fresh basil harvest out the vertical farm, enjoy!

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