Automated indoor horticulture for large scale commercial food production

Master thesis

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Abstract

Indoor cultivation by use of climate-cells provides a higher consistency, quality and more reliable method of producing fruits and vegetables in comparison to greenhouse cultivation. These aspects become increasingly important as we face the challenges brought by higher populations and climate change. However, currently the costs of indoor food production are far too high to compete on a commercial scale. In this report the costs and opportunities of indoor farming are analysed and used as basis for designing more costs effective implementations of climate-cells. Cost effective climate-cells can be achieved by producing more within the same system without compromising accessibility to the crops or making use of expensive automation and transportation solutions. This design project led to the development of such a system. The final concept enables a highly efficient method of producing crops on several layers while minimizing cost and complexity of transport and improving the longevity of expensive parts. Necessary further steps for the completion of this concept into an operational indoor climate-cell are left to the company Certhon whom supported this project.

Keywords:

Indoor cultivation; vertical farming; automation; transport; climate-cells

Table of Contents

1 Introduction

In the coming decades we are faced with two pressing changes; a rising population that is nearing 10 billion by 2050 (‘Health, Nutrition and Population Data and Statistics, World Bank | Population Dashboard’, 2019) and global warming. This leads to concerns about food security and availability, among other things. Food involves everyone, we literally cannot live without it. Throughout centuries, we humans strived to increase the yield and quality of any crop we consume by breeding them to our liking. Crop cultivation is an extremely competitive market, with little to no tolerance for error. This sector is always searching for new ways to grow more at a lower price, especially The Netherlands who is number 2 on agricultural export, measured by value, second only to the USA (Viviano, 2017).

Within the process of producing the vegetables on one's plate, multiple values have to be met to keep the end consumer satisfied and all those involved in the supply chain. Crop producers have to take numerous factors into account in order to keep their business financially sustainable while keeping their crops healthy. Producers of crops value secure systems with an ensured return on their investment. Any inconsistency in quality or price can lead to a wholesale buyer of produce to look elsewhere, meaning the seller has lost their main source of income. A second worry of the cultivator of crops comes from disease infested plants, which most certainly impact their yield and could be fatal to their business. Most growing in the Netherlands is done inside greenhouses, meaning the crops are only somewhat protected against nature, but are still susceptible to disease. Lastly due to urbanisation and an ageing population, the knowledge required for successful cultivation could be lost within following generations. Effective management of all the factors that come into play is not easily done nor learned, especially on the side of high volume production. These aspects push the horticulture market toward different approaches.

The horticultural sector is currently aiming at data driven and autonomous and vertical cultivation of crops indoors (without any outside influence). This provides optimal security and control since the environment can be tailored exactly to the needs of the plant and is shielded from outside influences. Uncovering these specific needs is essential to make this method of cultivation work, but require time, expertise and useful data. Besides the needs of the plant itself, it is essential to capture and adhere to the knowledge and needs of current cultivators to run future businesses effectively and provide them with valuable tools. Providing and combining these insights is valuable to new endeavours in both current and emerging markets who might lack the expertise, workforce and capital to increase their business in a financially sustainable manner. Opportunities thus lie in the correct integration of present knowledge, system hurdles and future implications into valuable and novel ideas for autonomous vertical indoor cultivation.

The project is executed with the guidance of the company Certhon. Certhon is vested in the greenhouse and climate-cell business. They provide new customers (the cultivators) with customised and highly specialised greenhouse or climate-cell solutions and are at the forefront of indoor cultivation.

1.1 Problem definition

There is currently no economically viable option for autonomous vertical indoor farming in a large scale commercial production of fruity vegetables according to Certhon.

Indoor farming is a method of cultivation that could make food more abundant and the supply more secure. This is achieved by using a so called climate-cell in which all environmental aspects can be tailored to the plants specific needs like lighting, nutrients and temperature. Which in turn leads to increased production and less environmental influences. Unfortunately it is currently far more expensive than outdoor or greenhouse cultivation, which often makes the financial risk too great and the return of investment too long or non-existent. Since the whole horticultural sector is experiencing a decline in workforce and expertise to run their businesses (Kurhade, Deshpande, & Dongare, n.d.), there is an opportunity to automate large parts of the process both decreasing the investment costs while reducing the need for labour.

Another benefit of growing indoors is its potential to grow far more on the same footprint. And, as more is grown in the same space, the added cost of the structure and land per kg of produce could be minimized. Production capacity of an indoor facility is based on the yield of each plant and the amount of plants per area (kg/m^2) with every additional layer the yield per m^2 increases, thus making more efficient use of the space. However, current production methods make labour more difficult and expensive, but this does not have to be the case if designed properly with automation in mind.

Currently, vertical and automated indoor systems are only viable if it is; research oriented, growing crops that do not require a lot of light and no manual upkeep like leafy greens or the crop has a high retail value (like cannabis or due to import costs), a heavily subsidized or funded project, placed in an area with low electricity costs or the land is expensive (making horizontal expansion less attractive). These factors all influence the costs versus benefits. For example, in the medicinal cannabis production cleanliness and safety are of utmost importance since patients are more prone to disease from plants (GreenChoices, 2018). Medicinal cannabis is also a valuable product meaning an indoor farm makes financial sense.

The combination of automation and vertical indoor farming could be key to make commercial indoor cultivation financially interesting. The need for climate-cells will continue to expand to regions where it is currently not economically viable as costs decrease and where the previously mentioned conditions do not apply. Next to that, the use of climate-cells could extend further into the supply chain or other markets as functionality and ease of use improves.

1.2 Goal and scope of thesis

The goal of this thesis it to propose a preliminary concept that provides the first step towards economically viable autonomous vertical indoor farms. More specifically for strawberry production in an economic climate similar to The Netherlands, which is used to estimate and evaluate ideas based on things like land value, electricity costs and labour cost.

The automation addresses the reduction of labour costs, lack of workforces and enabling more compact vertical farming than is currently implemented. Vertical farming is explored as a means to create additional value per area of indoor farm due to their high initial costs.

Figure 1: Certhon vertical indoor climate-cell for strawberry cultivation

1.3 Approach

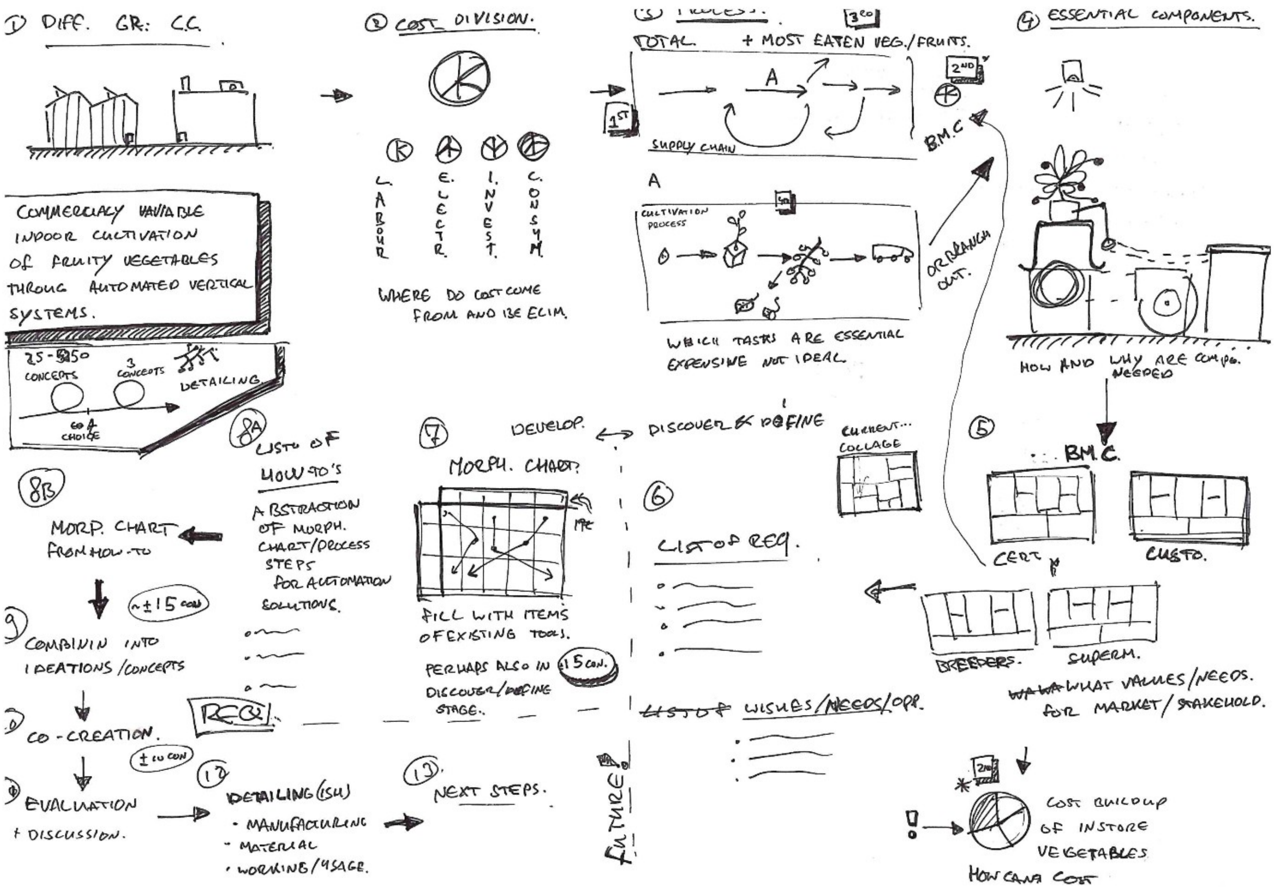

Figure 2: Project approach steps

The approach of this project roughly follows the stages of discover, define, develop and deliver. Each step requires proper exploration to make sure the following stage can be worked on correctly. In this chapter the process of each of these stages is described and is explained how the different methods used contribute to the final design (see figure 2). All steps and the information gathered and generated during the entire process will be presented in this report in order to make the readers aware of the process and thoughts that contributed to the final design and to convince them of the products necessity.

This project is executed under guidance from the company Certhon and uses their knowledge and pre-existing indoor vertical facility as a starting point (see figure 1).

1.3.1 Discover

The project regards commercial viability of automated indoor vertical cultivation. Therefore everything that has to do with cultivation needs to be well understood, at least on a general level, in order to know how and why the stated problem currently emerges. The discover phase will be filled with information acquired using the following (re)sources; interviews/conversations with Certhon employees, company visits in the sector, observations of processes, literature on cultivation and logically inferred statements.

First the reasoning behind indoor farming is explored (see 2.1 Greenhouses and climate-cells). The goal here is to understand what the differences are between indoor farming and current greenhouse cultivation. By making this comparison it becomes clear why and how one is different form the other. This logic can then be transferred to generate more complete designs using only the best from both.

Next comes the cost comparison to ensure future commercial viability (see 2.2 Running and investment costs). The price build-up of an indoor facility is the most important aspect in this project since the high investment and running costs are the main concerns that limit its implementation. Aside from a reduced pricing of the system, there could also be potential in shortening the supply chain and reduce margins in case the indoor cultivation is still too expensive after cutting cost. The stakeholders in the supply chain are thus also analysed to see where what value can be added or removed, further shrinking final costs (see 2.3 Stakeholders).

Once the costs are clearly explored the focus shifts towards the cultivation part of the project (see 2.4 Production process). Here the goal is to understand what is going on inside currently viable greenhouses in terms of the processes needed. Without proper understanding of the route necessary for high volume and quality produce there exists the chance of creating incomplete designs. For example, if a concept or proposal does not integrate or makes room for irrigation, the system could never work since plants require it to grow. Naturally, when looking into the cultivation process, a list of essential components can be made. This list of components also displays different methods that could be used to vary between parts of a design (e.g. a concept might become better when using another irrigation method).

Finally, current automated and vertical integration techniques within indoor farming (and different yet comparable systems) are explored in order to find out what is already there, how it is used and if it can work(see 2.5 Automation and vertical systems). This is then also incorporated into the morphological chart of the next phase.

1.3.2 Define

In the definition stage most of what has been discovered is distilled into the essentials. This means the information gathered should result in quantifiable requirements and a concise overview of variables (see 2.6 Requirements).

The requirements are used to adhere to necessities within the project. If an idea or concept cannot meet a requirement it is per definition not a viable idea. However, it is possible that a previously set requirement does not apply to a certain concept. Take for example a requirement that has to do with personnel safety inside/around the system. If a design has no need for a person inside/around the system, the safety requirement does not need to be met for that specific design. Also, the list of requirements is used as a tool to rethink ideas into proper ones (i.e. an idea that does not meet a requirement could be redesigned into a version that does). An additional list of wishes is created for possible features of a design which are not essential but valuable nonetheless.

1.3.3 Develop

In the development phase the concepts and vision of the product is worked on (see 3.1 Ideation), so that the delivery phase is well received by both the company as a product and university as a proof of competence.

First some initial ideation sessions (see 3.1.1 Brainstorm) are held to document and explore any ideas that arise during the previous phases. Due to the relatively large investment time of the previous two segments this partly occurs in parallel to them. In this way ideas have a range of 'naïvety' from not knowing a lot which produces more out of the box ideas, to being fairly familiar with the subject which produces more refined ideas.

After initial brainstorming, the morphological chart will be used to vary ideas further once the initial 'burst' of ideas has slowed. A morphological chart is used to explore all known possibilities within indoor cultivation in an overview separated by categories. Categories will include general sections like positioning of the crop and transport method, but also specific items such as type of substrates or irrigation method (see 3.1.2 Morphological chart for more details). Ideas can be either generated from scratch using the morphological chart or be improved upon or varied using the chart (i.e. taking a concept and searching within the chart for modifications or alternate implementations).

Conversations with colleagues will partly guide the process by indicating how and why certain things could or could not work. They can also contribute to more robust ideas. Logical evaluation is used to filter out any ideas from the brainstorm that are not viable at all. Here the comprised list of requirements also partly serves as a filter to get rid of insufficient ideas.

A pre-selection of concepts shall be worked on in more detail to be presented at a concept evaluation meeting in which the direction of the project will be decided on (see 3.2 Concepts). Depending on the results of this meeting one or two concepts will be worked on in more detail for final delivery. Parts of the final design will be prototyped and tested, serving as a first check to its viability.

The evaluation of the concepts will be done on three levels; logical reduction alongside the list of requirements and plus minus interesting (PMI) points stated per concept, weighted objectives using the highest rated features and finally deciding based on the companies personal needs/wishes (see 3.3 Concept evaluation).

At this point, due to the unforeseeable nature of design, a re-planning will take place that will dictate how to continue with the final concept. Any remaining concerns and uncertainties about the viability of the final concept are addressed in the concept detailing (see 3.4 Concept detailing).

1.3.4 Deliver

The project ends with the delivery phase, where the final product is shown in detail (see 3.5 Final concept). The level of detail required for this project by the company is a design proposal with the working principle explained, materialisation defined, the manufacturers explored and selected, installation/deployment specified, capabilities highlighted and usage instructions set. The report ends with the recommendations for the next steps to ensure the proper working and continuation of the final product. This includes which tests need to be performed and how the concept might be improved further.

The working principle shows what the product will look like inside a climate-cell using a 3D model with the shape and size of the core parts defined. The use of renders will further indicate the final look and feel of the concept. Later on the capabilities and usage will be mentioned.

The materialisation of the concepts is required since Certhon expects to be building the concept in the near future (1 year). This means materials, manufacturing methods and manufacturers will be stated so that it, indeed, can be built.

The installation of the product will be explained broadly to indicate its feasibility, however this does not necessarily have to be the actual way and it is assumed there is an insufficient amount of knowledge for the proper installation of the entire structure in regards to building codes and safety (thus also the sub parts).

The appendix of the report contains additional data like background and process information. Aside from the report, the CAD files of the 3D models will be handed to Certhon.

2 Background

The process of cultivation needs to be understood before diving into the redesign of vertical automated indoor farming. The following parts explain the background information in terms of: Greenhouses and climate-cells, Running and investment costs, Stakeholders, Production process and Automation and vertical systems. This information is necessary to understand the sector, set requirements and develop valuable novel ideas.

2.1 Greenhouses and climate-cells

Figure 3: Greenhouse (Certhon)

In The Netherlands a vast a mount of crops are produced in greenhouses (Wageningen Economic Research, 2018). These greenhouses provide partial protection from nature using a steel structure with glass panels (see figure 3) and are used to grow a wide array crops, while boosting the productivity of the land compared to open field agriculture. The success of the greenhouses comes from the mild Dutch climate which has relatively small fluctuations in temperature due to the nearby sea. Even though the focus of this project is on climate-cells (also called plant factories) a comparison will be made between the two, since greenhouses are currently superior for mass production of most crops compared indoor systems. Here the key differences between the two are discussed since that indicates what the positive and negative aspects of the two systems are and how to integrate them.

2.1.1 Greenhouses

Greenhouses (see figure 4) are quite different from climate-cells (see figure 5). A greenhouse is, in its simplest form, a glass box in which plants are grown. The glass box makes it possible for heat, CO2 and water to remain mostly inside while sunlight can still reach the crop for photosynthesis. This enables the farmer to change the climate to the plants needs, but it also means they are dependent on the weather for the performance of the crop and plants are exposed to diseases and pests. The use of artificial lighting and additional heating can extend and improve the growth and yield of the crop if outside weather conditions are not ideal, but this is expensive. When producing heat for climate control via a cogenerator, a lot of the additional heat is wasted due to the poor insulation of the glass. Also any added CO2 is lost when heat ventilation to the outside is needed, due to the greenhouse becoming too warm form solar heat. Managing a greenhouse climate becomes increasingly complicated with additional features like multiple shade screens, additional lighting, cooling towers, etc. This creates an overload of variables to manage.

Figure 4: Greenhouse inside (Certhon)

Figure 5: Climate-cell inside (Certhon)

2.1.2 Climate-cell

In a climate-cell the outside environment plays virtually no role on the climate management inside, this means there are always the same variables to manage. The structure is a sealed insulated box where no light can enter and where outside temperature has little to no effect. This also means that bugs, pests or other diseases cannot easily enter the building, resulting in overall improved plant health. With human labourers entering and leaving the cultivation chambers for upkeep and harvest it is possible for airborne diseases to enter. Therefore a disinfection zone should be integrated, people should wear clean suits and the chamber should be set at a slightly higher pressure to ensure air always flows out of the cultivation chambers. Since the climate-cell is a completely sealed box it does mean expensive artificial lighting is required. However, this provides far more control over the climate, improving the plant growth and making the plants less prone to diseases and pests. Unlike greenhouses, which are often heated by burning natural gas also providing electricity and CO2, climate-cells produce too much heat due to the efficiency of today's lighting systems. More than 60% of LED energy becomes heat and therefore climate-cells need to be actively cooled. However, with sufficient cooling, the height of the climate-cells can be lower since it only has to accommodate the plants and the people working inside, while in a greenhouse the extra height is used as a temperature buffer against weather changes which is needed to make climate control more manageable. In future endeavours this excess heat could become a non-issue when, for example, routing it to nearby homes that require heating.

2.1.3 Difference greenhouse and climate-cell

The biggest difference between a greenhouse and climate-cell is their costs. Greenhouses are cheap to build and run and climate-cells are expensive to build and run. This difference is still too high to convince growers that the added benefits of climate-cells like control, speed and security are not outweighing the additional costs. This added benefit has been useful to research related growing, breeders and leafy greens production, but for commercial growing of fruity vegetables both the investment and running cost are too high (Kozai & Niu, 2016). Investment and running costs of climate-cells can be as much as 15 times higher than greenhouses, though this can be compensated by the higher production volume of the plant factory. Tests have resulted in 92% increase in yield when growing indoors compared to greenhouses (Certhon, 2018), which primarily comes from increased light intensity and is not possible in greenhouses due to climate management limitations. The electricity costs of running a plant factory is also extremely high, since artificial lighting and cooling is required. In greenhouses this is not a problem because the light provided by the sun is free though inconsistent and the climate is more cost effectively managed by simply letting the air out. Some greenhouses do deploy some additional artificial lighting and heat dissipation systems, but require only a fraction of it compared to plant factories. For both systems a large chunk of the running cost goes to labour.

In short, the difference between greenhouses and climate-cells is their control over the environment versus costs. Greenhouses are far cheaper but plant factories are more stable and easily managed. Depending on the environment or goal of growing it is up to the customer which one to chose.

The costs of the climate-cell is the main reason for not being implemented on a commercial scale. Therefore they have to be further analysed on what part is so expensive and how they can be used more efficiently or removed. The next part, Running and investment costs, explains this in more detail.

2.2 Running and investment costs

Commercial viability of indoor farming is mainly dependent on how much it costs and how much it produces. It is therefore essential to take a closer look into the division of investment and running costs of horticultural systems. In this part, an overview of these costs is presented and explained how the components and processes relate to each other. Analysing these costs can provide insights on which parts are most expensive and where the most costs could be saved. All the graphs and information provided is an estimation and generalization based on experience from Certhon. Also, both investment and running costs can vary greatly depending on the needs of the client and the location due to differences in wages, electricity costs, climate, etc. Therefore, throughout this chapter, some statements are made to indicate how such differences influence the cost ratio, though most will be considered self-evident (e.g. lower electricity costs decreases running costs). Figure 6 shows the cost build-up of an indoor cultivation facility. This specific case is for strawberry cultivation of about 1 hectare and would costs around €900/m^2. The build-up of these categories is described in more detail in the following parts. The colours used in figure 6 correspond to the more specific cost divisions of figures 7, 8, 9 and 10.

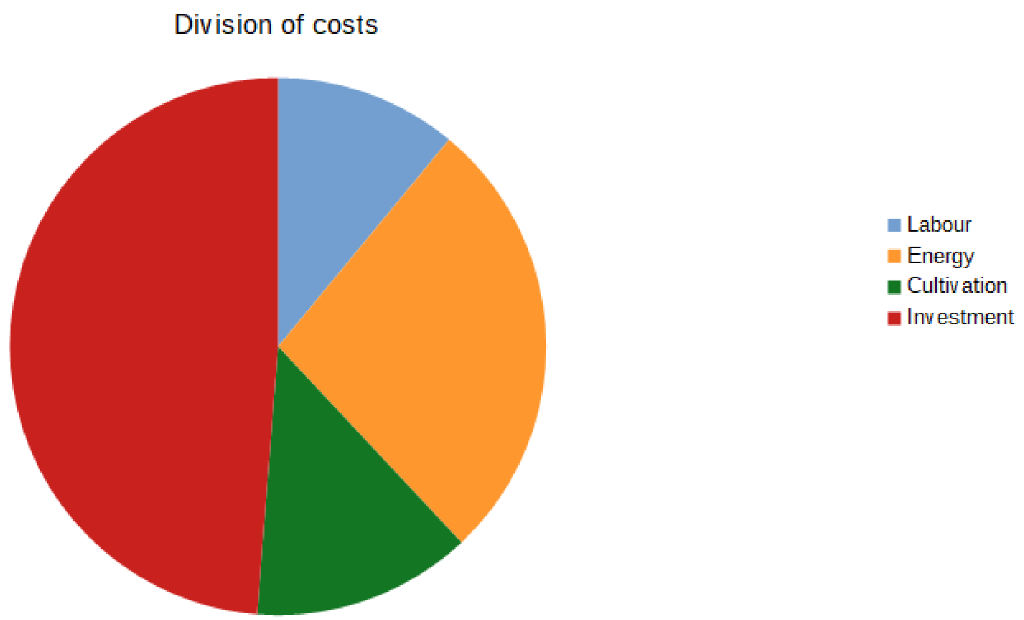

Figure 6: Division of costs climate-cell 1 hectare (derived from Certhon data)

2.2.1 Investment cost

Figure 7 shows a general indication of how investment cost are divided for a climate-cell derived from Certhon. The estimated investments depreciation is 10 years, so both running and investment costs can be used as cost per m^2/year. The investment cost for a Certhon climate-cell per m^2 usually range from €400 to €800

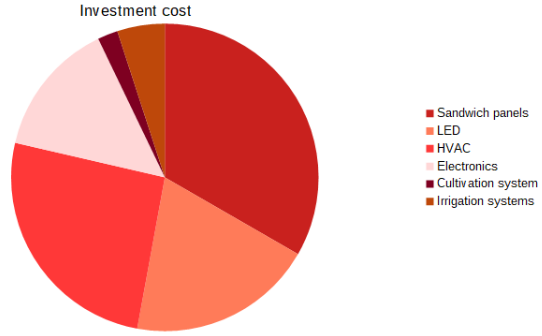

Figure 7: Investment costs climate-cell (derived from Certhon data)

or more. The main differences in the costs of plant-factories compared to greenhouses come from the more expensive exterior sandwich panels, artificial lighting and the required ventilation to cool the system. Greenhouse make use of inexpensive glass panels and use little to no artificial light and are thus within €50-200 per m^2. A climate-cell has to improve productivity and manage cheaper running costs if it should compete on the same level as a greenhouse.

Because of the higher investment costs needed for plant factories, it is especially interesting to look at the vertical space usage since every horizontal increase in size requires more land and expensive panels. Although left out in the investment cost, the land value also plays an important role. This project therefore also considers when which direction of facility size increase (horizontal or vertical) is the more economically viable choice. This is discussed in 2.5.2 Vertical farms.

2.2.2 Energy Costs

The second largest costs of plant factories come from the electricity consumption for the lighting (see figure 8). No sunlight enters the climate-cell, so all lighting has to come from LED strips. LEDs are by far the most used lights for indoor growing since they generate far less heat than other lights. This heat generated by the lights also needs to be cooled in order to keep the climate ideal for the plant. Unlike greenhouses, it is not possible or preferred to dissipate the heat to outside, since a sealed environment reduces the possibility of pests. However, there is no need for active heating since the heat generated by the LED is enough to keep the system warm even in extremely cold climates (Kozai & Niu, 2016).

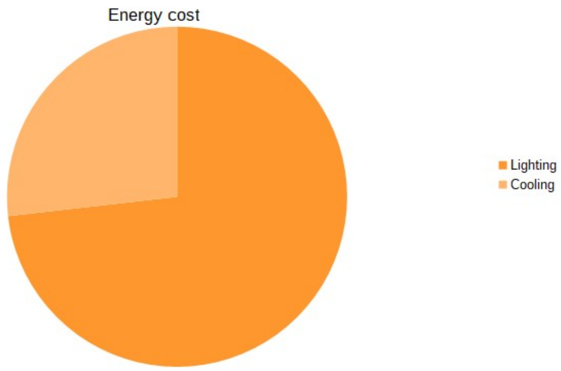

Figure 8: Energy costs climate-cell (derived from Certhon data)

Energy costs can be reduced in a vertical automated system if there is a more efficient usage of the emitted light. Currently, most cultivation systems have to take the human worker into consideration and thus have sufficiently large corridors integrated in the cultivation space for people to walk through. As a result part of the lighting does not reach the plants but the floor, wasting valuable electricity, generating more heat and requiring more lights to achieve the same illumination. Since there is a theoretical limit to the efficiency of lighting (part of the electricity will always be heat), in the future excess heat might even be repurposed elsewhere. For example, as central heating for housing, perhaps enabling an additional source of income.

Only a small percentage of the energy is used for the pumping of water and air circulation (5-10%) and are neglected in this case. However, the power required to pump water to a certain height increases as the system becomes taller and thus increases both investment and running costs. The amount of water that needs to be pumped also changes depending on the growing technique (see chapter 2.4.3 part Irrigation).

2.2.3 Labour Costs

The labour costs, though not the most expensive, can still make or break an indoor commercial operation and make up a significant part of the running costs. As seen in figure 6 the labour costs take 1/8th of all costs, most of which is harvest (see figure 9). If made obsolete through automation, reduced labour could cushion the added costs in other places like LED investment or it might make the cultivation space more efficiently used.

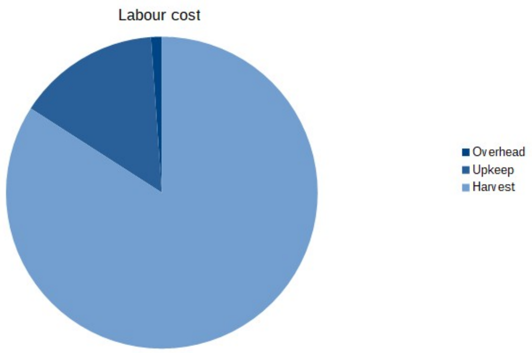

Figure 9: Labour cost climate-cell (derived from Certhon data)

Labour mainly consists of harvesting and upkeep of the plants with just a fraction required for overhead. The amount of hours needed for manual labour differs per crop since some crops require more care. All the steps required for the successful cultivation on a commercial scale are discussed in 2.4.2 Commercial cultivation cycle.

Automating labour should cut back on the costs, but is not realistic in all situations due to the 'complicated' tasks required for upkeep. The more complicated the task, the more complicated and expensive the machine that automates it will be and the further away the technology. However, as there are less workers available and wages increase, the willingness and need for labour reduction through automation also increases. More information of how automation can be of use in the design is discussed in 2.5 Automation and vertical systems.

2.2.4 Cultivation Costs

The cultivation costs consists of all the equipment, tools and consumables needed for cultivation (see figure 10). This includes substrates, seeds, seedlings, carts, etc. The costs of plants is by far the most expensive part. Most plants are first grown in a plant nursery focussing solely on the germination of seeds into seedlings and thus selling the young plant for further maturing and harvest. Since the substrate and fertilizers are consumed during the cultivation they have to be replenished at every new cultivation cycle.

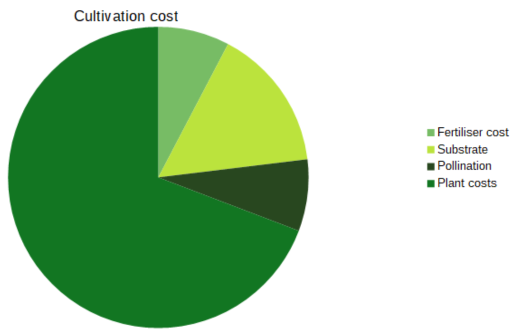

Figure 10: Cultivation costs climate-cell (derived from Certhon data)

2.3 Stakeholders

All stakeholders in the cultivation process contribute in some way to the final product. This also means that costs and value is added along this entire chain. The analysis of this process serves as an out of the box exploration of commercial viability by pointing out possible cost eliminations prior to or after the cultivation cycle. When an autonomous vertical indoor farm cannot be made viable for a cultivator it does not mean it cannot work somewhere else along the chain.

2.3.1 Supply chain

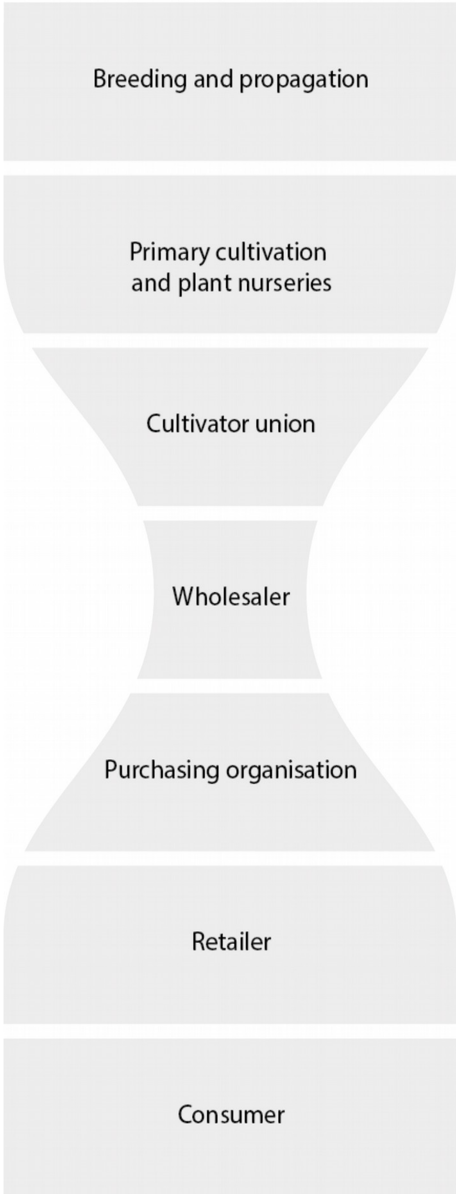

Figure 11: Supply chain fresh fruit and vegetables (LEI Consumer and Chain et al., 2018)

The supply chain of the horticultural industry in The Netherlands is quite streamlined and follows an hourglass like structure (see figure 11) with many producers or cultivators, a few or single collectors or wholesalers and many retailers (derived from LEI Consumer and Chain et al., 2018).

Figure 11 shows all different contributors in this supply chain and how they relate to each other. The exploration and understanding of the supply chain can help indicate where what value is added to the product and how and where costs can be saved, since it might be unnecessarily complex. Exploring the supply chain can also indicate aspects of the product or process that are a limiting factor for growth or increased efficiency and thus increase costs. The Netherlands already has a highly efficient supply chain so optimizing or redesigning it is not easily done. Nevertheless, the design of an automated vertical indoor system could be beneficial to actors within the entire chain and thereby shorten the chain or promote collaboration.

Breeding and propagation

The chain starts with the production of seeds and possibly the starting of seedlings and or grafting. The seeds itself are produced at large by breeders who continuously develop better plants with for example a higher disease resistance, different sizes, suitable to other climates, etc. Some plants are not grown from the seeds but from cuttings of other plants. Since these breeders put a lot of effort into creating superior crops, they are made in such a way that cultivators cannot simply regrow seeds from a previously grown batch. Instead they have to buy the seeds again once the growing season ends. All seeds that a breeder sells are genetically the same to ensure homogeneous production cycles.

Primary cultivation and plant nurseries

The cultivators grow plants to harvest and sell their fruits or other edible parts. They nurture the seed or seedling to a fully matured fruit yielding plant. A time which spans from a month to a year or more depending on the crop. Chapter 2.4.2 Commercial cultivation cycle explains this process in more detail.

For some plants there is a separate company for just the propagation of the plant, where the producer only grows the seed for a short period until a certain age. These so called plant nurseries then sell the properly germinated plants to cultivators. The added value is that all plants are growing properly meaning there is less fall-out in the rest of the production.

Nurturing from the seed could provide fewer initial costs since a partially grown plant is more expensive than the seed and keeps contamination from outside to a minimum. However this happens at the cost of possible plant fall-out and time. For this project and commercial indoor operations the plants should be grown from seeds since this ensures that no pests or bugs will ever enter the facility via plants from plant nurseries.

Cultivator unions

They cultivator unions serve to create more leverage against wholesalers and retail conglomerates and have more insights to get fair pricing by bringing different cultivators together. Without a union, the wholesaler or retailer can too easily switch to different producers if the cultivators cannot keep up with their demands. The unions sell the collective produce to wholesalers or retailers. Recently, as explained during a visit at cultivator union Harvest House, some unions have also added sorting, packaging and transport to their business shortening the supply chain and creating more leverage against retailers.

Wholesalers

Wholesalers buy produce either directly from the cultivator or a cultivator union. They are often the connection between large scale commercial producers and retailers. They make sure the food is cleaned if necessary, sorted by quality and or size, packaged to the retailers wishes and send to the respective locations. Food that is not up to standard can be either processed or cut to be used for instant meals or sauces, but this requires a sufficient volume of ‘leftover’ food.

Purchasing organisation

Purchasing organisations are often used to bundle the orders. This allows retailers to buy in larger batches for multiple branches.

Retailer

Retailers display and sell food directly to the consumers. They value the attractive display of food towards their customers and set a high standard for uniform quality food. This does mean that part of the food which is perfectly suitable for consumption is rejected and thrown away when it is not the correct size, shape, colour or exceeds the expiration date.

Consumer

The consumer is the final step in the supply chain. They are the ones for which the product is made. Most consumers want fresh, good looking, long lasting and cheap products. Besides this the customer values sustainable produces and the proper experience. This can be used to the store’s advantage, if it uses the ‘experience as an economic offering’ (Pine & Gilmore, 1999). If a product were to be grown locally at the store itself it could be presented in a way which entices the consumer to interact with and eventually buy the (more expensive) product and experience that comes with it. A vertical indoor farm is thought of as cool and exiting technology which can make people keen to see in action and willing to pay more.

For example, having a glass wall in the climate-cell can show people where their product comes from and provides a unique experience to that specific store. Even though the product might be more expensive this can be made up for by the experience, local produce, freshness and overall superior quality. It is important for retailers (and Certhon) to truly showcase these unique selling points and opportunities.

2.3.2 Price structure

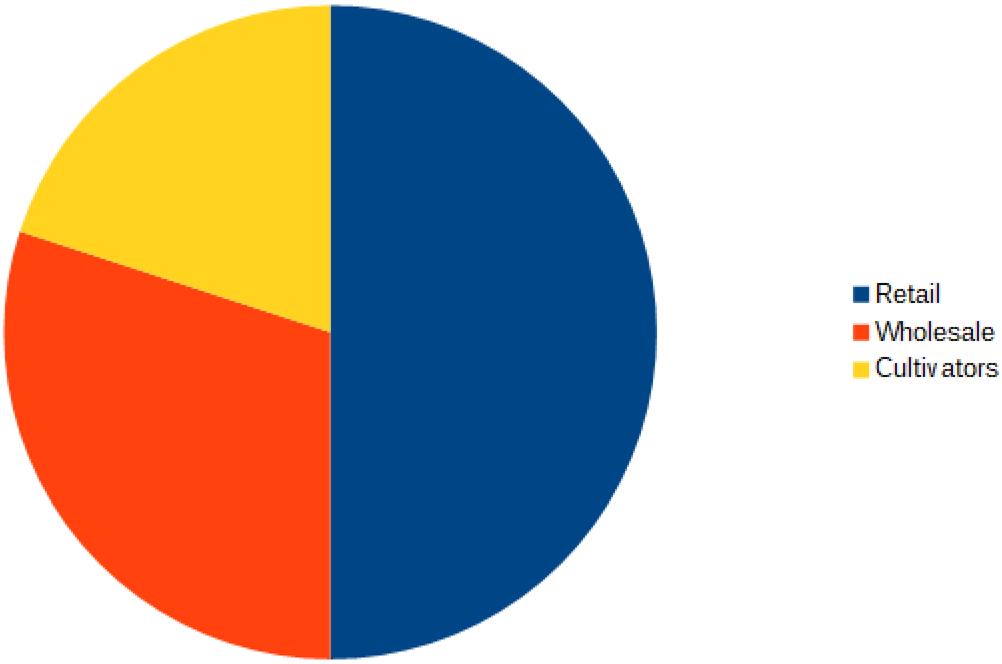

Figure 12: Price build-up retailed fresh fruits and vegetables

Figure 12 shows a generalised price build-up between the three main stakeholders of the supply chain. The chart represents the cost of the product and the different colours show what part of the costs are made or added by which party in the supply chain. The cost build-up consists of 40-60% for retail, 10-40% for wholesale and 20-35% for cultivators (LEI Consumer and Chain et al., 2018). Meaning, when a fruit is sold in the store by the retailer for €1,- the cultivator sold it for €0,20 and the wholesaler for €0,50. Often times the cultivators account for the smallest portion of the price build-up while being the ones adding the most value (making the actual food/product) and investing the most time. They have to care for the plants over several weeks or months and manage the quality, while wholesalers merely put a package around it and the retailers just present it in a store.

The selling price for the cultivators are determined every week according to the market or determined by contracts. Rising or lowering prices generally impact consumer pricing though with some delay, which indicates a proper market dynamic. In 2.2 Running and investment costs, costs of producing the vegetables and fruits has already been explained in detail. For the wholesalers the added costs come from labour (10-30%), facilities (2-10%) and mainly transport and packaging (70-90%, of which transport 30-40% and packaging 25-40%).

The price structure presents a valuable insight related to the eventual user of the climate-cell. An increase in cost per product is relatively far more expensive for the cultivator than for the retailer. This means the retailer might be more willing (given the right circumstances and system) to invest in their own production facility, thereby also compensating the added production cost by avoiding the price build-up from the supply chain. The business models discussed in the following chapter explains partly what could be done to the climate-cell to make it more attractive for the retailer and how they can serve as a plan B when costs of indoor cultivation cannot compete with greenhouse cultivation.

2.3.3 Business Models

The business model canvas is used to acquire a better understanding of the current businesses of the main stakeholders. It can help with analysing strong and weak spots, strengths and opportunities within the business and see the economic and contextual relevance of the product to be designed (Osterwalder, Pigneur, & Clark, 2010;Van Boeijen, Daalhuizen, Van der Schoor, & Zijlstra, 2014). Here various business model canvasses are shown that indicate the different standpoints of key contributors in the horticultural sector that influence the success of indoor farming on commercial scale including Certhon, Cultivators and retailers.

Certhon

Table 1: Certhon business model canvas

<table>
<tr>
<td rowspan="2">Key partners

irrigation suppliers

manufacturers for structure parts like extrusions, panels, flooring.

Sensor/electronics/ system suppliers like Phillips, Festo

Transport companies for delivery and export</td>
<td>Key activities

Building high end greenhouses/climate-cells

Consultancy and advice for greenhouse projects</td>
<td rowspan="2">Value proposition

Providing climate controlled greenhouses and climate-cells specific to location, cultivation and cultivators needs

Insights and secure</td>
<td>Customer Relationships

Detailed and ensured quality for greenhouse and climate-cell projects for new customers

Advice on cultivation and climate control for cultivators

Flexibility and control for research institutes</td>
<td rowspan="2">Customer segments

Cultivators

Universities and other research institutes

Breeding facilities (research oriented)</td>
</tr>
<tr>
<td>Key resources

Warehouse / workshop for structure building</td>
<td>Channels

Mouth-to-mouth
Website
Business fairs</td>
</tr>
<tr>
<td colspan="3">Cost structure

Workers and labourers for build processes

System design for customers with varying needs worldwide to ensure quality and low costs

Invoice setup expected and detailed costs estimations during the process

Research and design to anticipate upcoming changes in the horticultural sector and provide ensured costs estimations / production quantities</td>
<td colspan="2">Revenue streams

Sales and construction of greenhouses and climate-cells

Maintenance and consultancy

Research for cultivators</td>
</tr>
</table>

This model (see table 1) is based on the perspective of Certhon and derived from several interviews and conversations with their employees (see appendix 5.2 Questions). This business model indicated which values are important to Certhon and how/where this project can add more value.

The main activities of Certhon regard the selling and building of greenhouses. After that comes consultancy and support of existing customers/cultivators. Besides this, research and development toward new and enhanced growing techniques and practices is used to stay ahead of their competitors.

This project contributes to their research and development, focussing on designing a more economically viable climate-cell by increasing the productivity per volume while keeping the costs low. Economically viable indoor cultivation adds to Certhon revenue stream since as of now only relatively small scale indoor projects have been realised compared to their greenhouses.

Cultivators

Table 2: Cultivator business model canvas

<table>
<tr>
<td rowspan="2"><u>Key partners</u>

Breeders
gas, electronics companies

Wholesalers/ cultivator union/retailers

System mechanics/advisors/ consult</td>
<td><u>Key activities</u>

Harvest, upkeep and maintenance

Quality control for crops</td>
<td rowspan="2"><u>Value proposition</u>

Producing high quality fruit/vegetables for human consumption</td>
<td><u>Customer relationships</u>

Reliable production consistency</td>
<td rowspan="2"><u>Customer segments</u>

Customers looking for consistent low priced quality vegetables</td>
</tr>
<tr>
<td><u>Key resources</u>

Electricity, water and gas

Labour for harvesting

Transport</td>
<td><u>Channels</u>

Via cultivator unions
Word of mouth</td>
</tr>
<tr>
<td colspan="3"><u>Cost structure</u>

Labourers for upkeep and harvest of plants

Investment in greenhouse / climate-cell build and maintenance

Consumables like electricity, natural gas, CO2, plants, substrates, etc. for climate control and production</td>
<td colspan="2"><u>Revenue streams</u>

Selling of produce to wholesale and or retailer</td>
</tr>
</table>

The cultivators (see table 2) are the current and future customer for Certhon their climate-cells. Without a proper understanding of the business model of cultivators one cannot properly adhere to the user’s wishes. Since cultivators provide to retailers and wholesalers their main interests lie in producing quality produce with consistency. The required investment in a climate-cell is currently far higher than a greenhouse, so the return on investment and the added benefits should be apparent with regards to quality and consistency. Their cost structure, as described in chapter 2.2 Running and investment costs, mainly consist of labour, investment and consumables. Cultivators already experience a decline in workforce and pressing climate regulation which will increase their costs structure, so they will likely have an increasing interest in development and innovation toward autonomy and more efficient use of resources.

Retailers

Table 3: Retail business model canvas

<table>
<tr>
<td rowspan="2">Key partners

Transport and distribution centres

Cultivators

Job agencies</td>
<td>Key activities

Properly displaying fresh products

Cooking healthy meals on locations

Managing stock</td>
<td rowspan="2">Value proposition

Sell authentic cheap products

Provide healthy convenient meals</td>
<td>Customer relationships

In-store
Fast and personal service
Help desks</td>
<td rowspan="2">Customer segments

Mass market</td>
</tr>
<tr>
<td>Key resources

Buildings / facilities
Warehouses
Cashier and stocking Clerks</td>
<td>Channels

Online advertising
(TV) advertising
Folders</td>
</tr>
<tr>
<td colspan="3">Cost structure

Facility running cost
Employer costs
Product/stock management</td>
<td colspan="2">Revenue streams

Product margins
Product placement (branding / promotion stalls)</td>
</tr>
</table>

Table 3 is based on the business model of retailers and is partly filled using information acquired during an informal interview with a Jumbo branch manager. However, most aspects from this business model become apparent when simply walking through a store. We talked about the constraints which prevent or slow down the cultivation of food ‘in-store’. The reason for the interest in the retail business is the large difference between the retail selling price and cultivator selling price. Simply said, the retailer functions as a plan ‘B’ in case indoor farming is not an economically viable option for commercial production using the traditional supply chain route. As shown in the previous chapter the price of fruits and vegetables increases up to five fold along the supply chain. By cutting out the suppliers and cultivating locally themselves using a climate-cell, retailers can sell produce without any added marginal costs of other businesses while producing superior fresher fruits and vegetables. Aside from this they have a closer influence on the final consumer to perhaps steer them into a willingness to pay more for a premium product.

In The Netherlands the consumer generally wants the cheaper product and are often not willing to pay higher prices. However, according to the Jumbo branch manager, some people are willing to pay more for superior products if it is better know how it came into the store, e.g. its origin, makers, how sustainable it is, etc. Retailers need a way to prove, convince and inform about what exactly is in their stores. A climate-cell can become an additional way to show this information. A store in possession of an indoor farm that the mass market can directly see and possibly interact with shows exactly what is needed for them to buy the premium. This does not even need to be the case since some fruits are already sold for a higher price in-store than its production cost in a climate-cell (see appendix 5.10.2 Cost production strawberry).

2.3.4 Stakeholders key insights

Fruits and vegetables, when travelling through the supply chain, become increasingly expensive without a lot of added value. Shortening this supply chain can be beneficial for the price of the final consumer product and might make the added benefits of an indoor farm more attractive. Adding autonomy and vertical growing to its features can also make retailers interested in growing their own, because of the added reliability, ease of use and higher produce per square meter. There have been instances where a retailer showed interest in growing their own, but commercial cultivation still depends on the expertise of cultivators for optimal produce. However, retailers have better insights in their customers wants and needs and can thereby tailor their production to suit them or market specific produce. For example, estimated overproduction or overripe production can be discounted achieving less wastage in smaller productions or less attractive produce can become less of an issue through marketing. Not all cucumbers have to be perfectly straight and of a precise length to taste good.

On the other side of the chain where plants are bred, large scale production could perhaps create additional income by sharing data and experience that can contribute to improved plant breeds. Since the volume in commercial production is a few orders of magnitudes higher and naturally distributed, development could be sped up and variety increased.

Example cultivator shift

Ideally most if not all crops would be produced by retailers, since they stand closest to the consumer and can truly adhere to and influence their wishes. This can happen in store where customers can see and maybe interact with the plants grown inside the climate-cell. Another way could be to produce near the distribution centres of the retailers. Especially those that do delivery only, like Picnic. The reason being that the land value of these industrial locations is lower than in the city and no transport logistics are necessary.

The system would be tailored to produce consistently on a daily or weekly basis. Retailers could vary with the different cultivars of crops they use and get feedback on overall taste from the consumers. Additionally, the problems that occur during the growth cycle and preferable features of the plant can be sought after during the production in store using technologies for data collection that are relevant to plant breeders.

The space that is necessary to grow enough produce can even be quite small. By dividing the amount of kg consumed per person per year over the amount of kg produced per m^2 per year for any given fruit or vegetable an estimate can be made as to how much square meters is required in total. This number can then be divided over the number of stores nationwide, giving a rough estimate on area per store for that type of plant (not taking different store sizes into account). For example, the production of block-pepper and cucumber only requires a combined area of around 450 square meters on average per store (see appendix 5.10.1 Area per crop). Also, when growing vertically the area required becomes even less.

Unfortunately more space required for all the other crops that are commonly sold in retail stores, which would quickly increase the total required growing area. However, more perishable products and small plants like strawberries could be interesting. With other produce being located near retail distribution centres.

An argument can be made for advocating the most locally produced method: Do It Yourself (DIY). But this is not considered a viable alternative since not everyone has the time, skills nor resources to do so. And those who do may simply not be interested or bothered. Automatisation could be a solution but is too expensive for a DIY scale endeavour. So an alternate mass production is preferred.

2.4 Production process

2.4.1 Plants

Before going to the in-depth explanation of the horticultural process, it is important to have a general understanding how plants work. The design can, to a certain extend, influence the plant, like cutting leaves to make room for worker to walk through rows of crops. But, the plant influences the design as much if not more, since it sets the general boundaries regarding the shape, size and process required. Any farm could never be viable if the plants reached the ceiling before being ready to harvest for example. Also, certain plants are more suitable to indoor cultivation (for various reasons) and could inspire the breeding of plants currently not suitable for commercial indoor cultivation into one that is. Meaning the plant and process could be designed in parallel. This analysis allows for a better understanding of why processes described in chapter 2.4.2 Commercial cultivation cycle are done in a certain way and order and shows which parts of the process are essential and which are unnecessary for an automated vertical process.

Growth

In nature plants arise from the seeds coming from the fruit. This fruit arises once the plant has grown sufficiently and environmental conditions are right for flowering and after pollination. This is an annual process that repeats as long as each step is successful. What part of the crop is eaten depends on the crops. Plants vary on different aspects such time to maturity, amount of fruits, taste, etc.

In commercial production, longer growing plants like tomato’s and block peppers are cut and suspended from a wire to enable labourers to reach the crop better and to extend the yield period of the crop. The plants naturally want to grow into a bush like structure and produce their fruits all at the same time. Figure 13 shows what happens if you let a tomato plant grow without any cutting and stringing and figure 14 shows how it is grown in greenhouses. Inside a greenhouse a better overview of the fruits is kept by cutting and stringing the plants making harvesting easier. The whole process of commercial production is described in 2.4.2 Commercial cultivation cycle.

The natural size and shape of different crops have to be taken into account when designing an automated vertical system. Since no plant is alike, this would likely result in different systems for different plants.

Figure 13: Naturally grown uncut tomato plant (Wild Gourd Farm, 2012)

Figure 14: Commercially grown tomato plant (EasyPonic, 2016)

Nutrients and needs

Plants require an array of different nutrients in order to mature. The quantity of these nutrients depends on the plants. Plants take up nutrients with their roots from fertile water or soil and can therefore be grown with and without soil. The upsides of growing soil-less are that it shortens the growth cycle and increases the plant yield. Nutrients can be divided into two groups: macro nutrients and micro nutrients. As the name implies, macro nutrients are required in large quantities and micro in small. Nevertheless all are important for the proper growth of the plant. In general plants require the following macro nutrients: Nitrogen, Phosphorus, Potassium, Calcium and Magnesium and micro nutrients like Iron, Boron and Manganese (Kozai & Niu, 2016). These nutrients are divided among two different nutrient tanks to prevent precipitation, since al nutrients have to be present in ion form. When the plant lacks nutrients it expresses that in a certain way often visible with the naked eye under natural lighting. The nutrient solution has to be flushed out of the system every so often (weekly, depending on crop and size), since not all nutrients are consumed at an equal rate but are supplied constantly to promote optimal growth. Slowly the lack or excess of nutrients increases in the solution which can become toxic for the plants resulting in the need to flush and replace all water in the system.

Usually the cultivator inside a greenhouse can tell what a crop needs by looking at it together with measurements on environmental factors. This is more complicated in an indoor farm (as discovered by Certhon) partially because the lighting, when adjusted to efficiency, emits a purple like colour which makes assessment by sight harder to do. This means having white light present in the plant factory is required for visual assessment. However, Certhon also indicated that, even though professorial cultivators considered the look of the plant in their system unhealthy, there have been far higher yields compared to greenhouse production. This shows how little is actually known about the optimal cultivation of crops.

Breeding (for indoor cultivation)

Within nature exist genetic varieties. This means different species show different characteristics like size, shape, fruit, colour, etc. These varieties can be used to our advantage by breeding those plants or species with the characteristics that we prefer and leaving out the ones which show bad traits. This can thus result in crops being resistant to certain diseases, bearing larger/smaller/sweeter fruits, able to grow in different settings and much more. Breeding can be done across different but compatible species, which creates a hybrid. By creating a hybrid there exists a chance of incorporating those traits which were favourable in both parents. However, this involves a lot of trial and error. Also, depending on the crop, breeding can become more complicated e.g. strawberries are far tougher to breed than tomato due to gene complexity.

A successful indoor system depends on two things: the correct design for the plant and the correct plant for the design. This means that it is not only possible to make the system more suited for a certain plant species, but it is also possible to alter plants to better suit the design. A ‘low level’ example of this is the trimming of leaves and wiring of the tomato plant to make it better suited for harvesting. Another way is to breed or genetically engineer the plant to make it better suitable for indoor automated production.

2.4.2 Commercial cultivation cycle

Figure 15 shows the generalised process of commercial greenhouse cultivation. This process tree is derived from various literature, interviews and observational studies which can be found in the appendix (see 5.3 Cultivation additional information). The cultivation cycle is discussed in this chapter. Proper upkeep is needed for optimal produce so the design has to allow this upkeep to happen according to the crop's wishes.

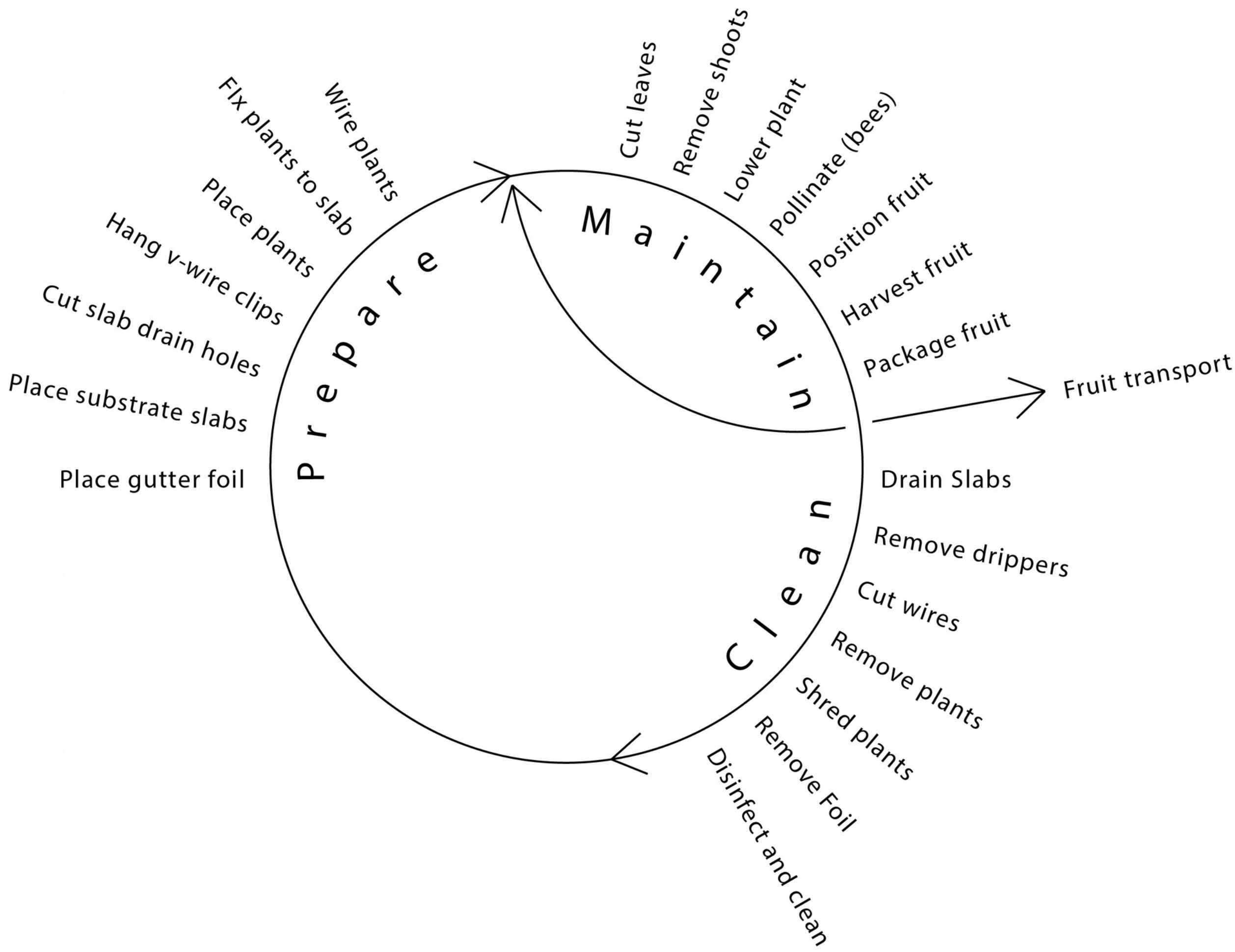

Figure 15: Cultivation cycle

In a commercial setting the cultivator start their process in one of two ways. Either from the seed and growing the whole plant, or starting from a partially grown plant. The cycle in figure 15 shows the latter. The only difference in growing from seed is an additional propagation stage where the seeds are grown into small plants and relocated to a bigger cultivation area often in multiple steps. The specific way of growing depends on plant species and the cultivator's preference and expertise. For commercial plant production, a germination percentage of 98% or higher is required (Kozai & Niu, 2016).

Prepare

The preparation phase consists of all the actions required to start the cultivation. Here substrates, irrigation and plant support is installed for the plants to grow in a manner which suits the cultivator. Depending on the plants there can be differences in the tools and actions needed. For example, tomatoes require supporting wires to maintain an upright position but strawberries do not, since they are a lot smaller. Instead strawberries sometimes have wires wound alongside the gutter to support the fruits.

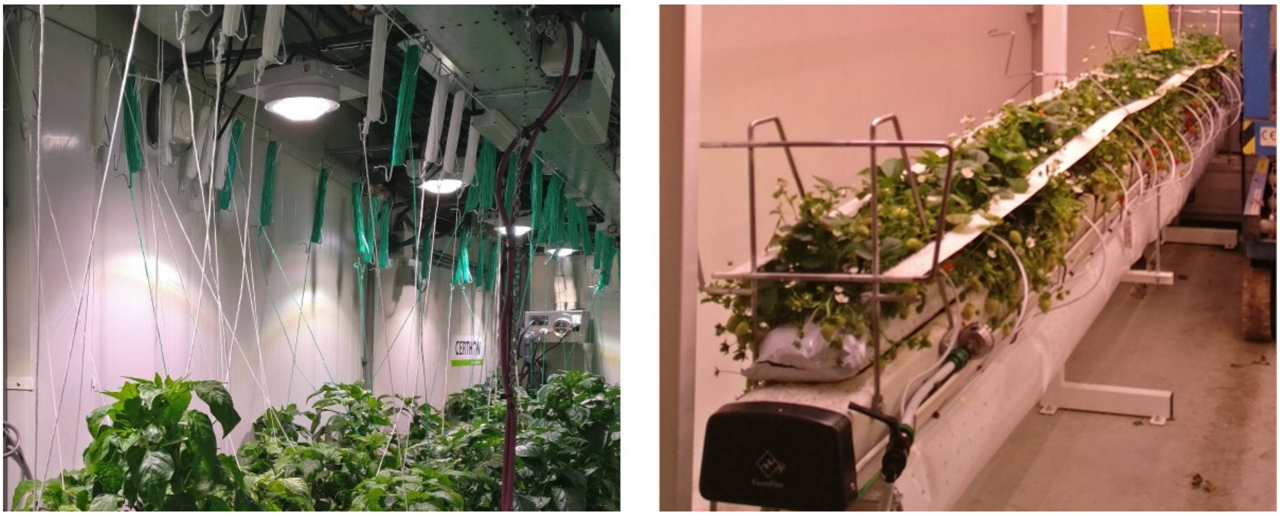

Figure 16: Different types of plant support (Certhon)

Maintain

During the maintenance phase the plants are kept in a shape which is most suited for upkeep and harvest while controlling the environment to best suit the plant. Shaping the plant in a way that present a clear overview of the fruits is preferable to the speed of the upkeep. Here leafs are cut, vines wound and lowered and fruit is supported. Most ripe fruit is harvested and packed, the fruits which do not conform to the quality standards set by the cultivator or retailer are discarded. Picking often happens within the growing chambers, so there are pathways between the rows of plants for workers to walk through. Some systems make use of transportable gutters or similar, that move the plants to the worker. The maintenance cycle happens continuously until the plant has reached peak productivity and is no longer financially interesting to grow (usually less than a year for fruits and vegetables).

Clean

In the cleaning stage all organic material and consumables are removed for the following production run. Here the plants and substrates are removed while the irrigation components are often re-used. The entire hall needs to be sterilised and thoroughly cleaned to prevent any pesticides, bugs or diseases from transferring to the new plants.

2.4.3 Climate-cell components

A climate-cell consists of various components. These components all contribute to providing optimal conditions for the plant, from nutrition to humidity and temperature. Here, these different components are shown and their purpose or workings are explained.

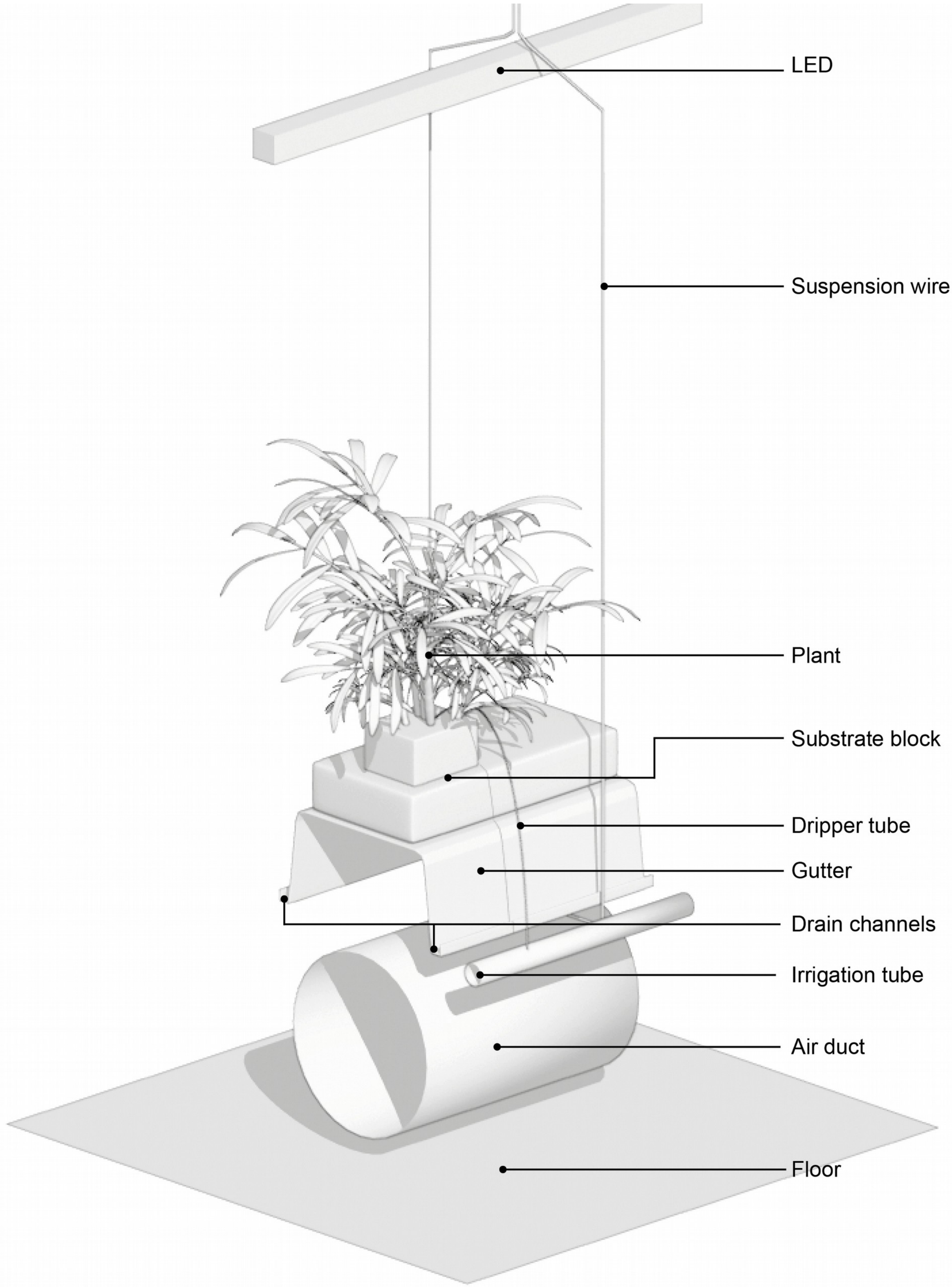

Figure 17: Gutter system components.

Figure 17 shows the main components for on gutter cultivation, the plants with substrate are placed on the gutter and are irrigated via tubing. Having an overview of the parts that go into an indoor farm provides a reference to use parallel to developing novel and useful systems. If one, for example, were to design a system without the LED lighting present it would fail to meet the system's criteria, having the main components at hand prevents this.

Exterior

Flooring, walls and ceiling

Walls and ceiling serve to protect the internal equipment against nature (to some degree) and to support anything that needs to be suspended (like plants, lighting, sensors, etc.). Plant factories are made of sandwich panels or other insulating materials. In a greenhouse sunlight is required so these panels are made of glass or plastic (which do not insulate well). These panels reside in a structural frame that supports the weight. The roof is held up by pillars with the gutters for the plants placed between them. A vertical indoor setup can use the pillars as fixtures for gutters on multiple levels, for greenhouses this would prevent the sunlight from reaching the bottom plants.

There are specific reasons a greenhouse looks the way it looks which do not necessarily apply in a climate-cell. For indoor farming it is still unknown whether to adhere to a building structure similar to a greenhouse that is optimised for letting the most light in or look at other layouts and methods like warehouses that are optimised for packing density and capacity.

Climate

Ventilation

Ventilation is required to provide sufficient airflow for the crops and is partially used to manage the climate. Airflow encourages gas diffusion in the leaves resulting in enhanced photosynthesis and transpiration and thus growth. Insufficient airflow can result in mould build-up and rotting due to the microclimate around the plant.

Cogenerator

A cogenerator (combined heat and power) uses natural gas or oil to generate heat, electricity and CO2 this is all needed in order to create the optimal conditions for growing. Cogenerator is not needed in a climate-cell due to the already excessive heat present, but is needed in greenhouses. This could mean that there is no need for a natural gas connection and the system would only run on electricity.

CO2 addition

CO2 is used by the plant for photosynthesis and so increasing the amount of it in the air increases the productivity of the plant to a certain amount. This increase can be realised by either burning fuel with a cogenerator or via liquid/gas CO2 tanks. There exists a saturation point for plants that, once reached, will not improve the growth.

Cooling unit

The temperature inside a plant factory needs to be regulated since plants perform differently depending on the climate. The lighting inside a plant factory is always producing additional heating due to their efficiency. This heat needs to be cooled to prevent an overly hot climate. As seen in the cost build-up cooling contributes to 25% of the electricity costs. So proper management is key. It is also interesting to note that plants who can handle warmer environments require less cooling, which could be interesting for climate-cells (which always have excess heat).

The cooling unit can also be used for dehumidifying. Dehumidification works by cooling the air until the water starts to condensate from the air., since cold air can hold less water. The cold air is then heated to the right temperature making it less humid. As all environmental factors, the humidity needs to be regulated to suit the plant needs. Once it becomes to humid in the climate-cell the plants cannot transpire enough and water starts to condensate on cooler parts. If the cooling unit cannot sufficiently dehumidify, an additional dehumidify unit has to be integrated. The amount of dehumidification has to do with the amount of plants in the room and their respiration at the specific growing temperature.

Irrigation

Irrigation is required to supply nutrients to the plants. Irrigation regards all parts needed to allow a plant to grow which included irrigation method, substrates and substrate holders. In figure 18 the most common types of irrigation are shown.

Irrigation methods

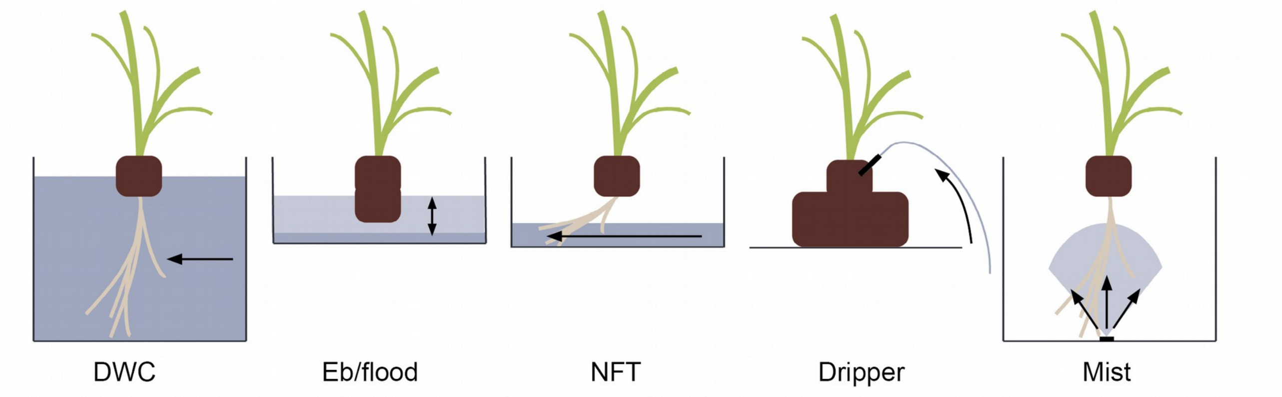

Figure 18: The different horticultural irrigation methods with arrows indicating the water flow

Deep water culture (DWC)

Deep water culture growing involves a bin/trench filled with nutritious water of +25cm. The roots of plants are submerged in the water to take up the nutrients. Plants often float on the water via a styrofoam raft or similar foam like materials. The raft contains holes in which small baskets are placed to allow the plant roots to reach the water. This method is popular for growing lettuce and other leafy greens commercially since the rafts can be placed at one end of a trench and taken out at the other, during which the plant grows to full maturity.

Ebb and flood

Ebb and flood concerns the rising and lowering of the water level in a tank for plants. The ebb and flood movement allows the roots to be drenched in water during the ‘flood’ while draining and taking up oxygen during ‘ebb’.

Drip irrigation

Drip irrigation uses dripper sticks along which the water flows into a substrate. The sticks are placed into a substrate and water is channelled to the sticks via tubing. The substrate soaks up the water coming from the drip sticks so the flow of water is not continuous. Sticks usually serve a second purpose of fixing rock wool of the seedling to the rock wool which rests on the gutter.

Nutrient film technique (NFT)

The nutrient film technique is similar to deep water culture though only small part of the roots are submerged. This requires a constant stream of water, otherwise the gutter will run dry and the roots cannot take up nutrients.

Aeroponics (mist)

Aeroponics makes use of a nutrient filled water mist that is directly sprayed on the roots of the plant. It is similar to drip irrigation in terms of components only instead of dripper the plants have mist nozzles. The roots are often suspended in the air above the nozzles without any substrate.

Substrates

A substrate is that in which the plant grows its roots. Substrates come is all sorts and sizes, the most popular of which are shown here (see figure 19). The most apparent is soil, yet the most commonly used in horticulture is rock wool. Depending on the plant different substrates are used. Things like root size, irrigation or cultivator preference can be a determining factor.

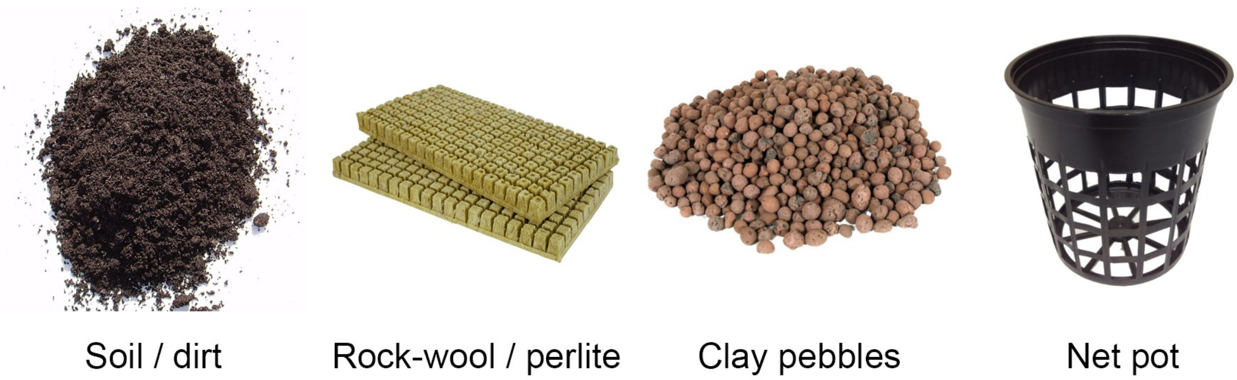

Figure 19: Different cultivation substrates (retrieved from BYJUS, n.d.; Hort AMericas, 2015; Hydro Crunch, n.d.; Orchidnuts, 2018)

Rock-wool is commonly used in greenhouse cultivation since it can hold water quite well while allowing the roots to grow for a prolonged period without deteriorating the material during use. Small rock-wool plugs can be used to grow seeds into after which they are transferred to a net pot (for NFT or DWC) or bigger substrate slab (for drip irrigation or ebb and flood systems).

Other types of substrates aside from the ones shown in figure 19 can also be used, however they would be comparable to the ones already shown with difference irrelevant to this project (like influence on water pH, etc.).

Substrate holders

The substrate holder is that on which a plant together with the substrate is placed (see figure 20). Often these are gutters or tables, but a simple floor is also sufficient for plants grown in pots for example. The main function of the substrate holder is to fixate the plant and substrate in place, keep the plant at an ergonomic height and to channel the nutrient stream for reuse (like a drain).

Floor Gutter Table

Figure 20: Different cultivation substrate holders (retrieved from Meteor Systems, 2014; Nexus Corp, 2019)

Tables and floors are used in ebb and flow systems where the plants can be submerged in water every so often. Gutters are often paired with drip irrigation or NFT and makes use of cocos or rock-wool blocks to hold the water for longer periods without continuously supplying water (like a sponge).

When using gutters the plants and are often suspended from the ceiling by wires. Depending on the gutter they can stretch a distance of around 5 meters without support and be hundreds of meters long (Meteor Systems, 2019). At these lengths the forming of the gutters can happen on location (*Meteor Systems*, 2015).

Fresh water inlet

A fresh water inlet is needed to keep the right amount of water in the system. Water is used to dissolve the nutrients into. Nutrient solution has to be flushed every so often so new water is required. Also, as the plants grow they evaporate and take up water. This water also needs to be replenished. The water is transported via tubing to each gutter and gets collected for recirculation.

Nutrients and nutrient tank

Nutrients are supplied in nutrient tanks (often divided into 2 separate ones). These nutrients come in concentrated solutions and have to be watered down and pumped into the system in correct quantities.

Electra

Lighting (LED)

LED lighting is used to provide lighting for the crops (see figure 21). It is mostly positioned above the crops (top-lighting), but can also be positioned between the crops (sidelights). In a greenhouse artificial lighting enables an extended growing period into the winter and an earlier start in the spring. For climate-cells it is essential to have lighting since no sun light enters the building. Lights are mostly suspended from the ceiling by wire or bolted down. They hang fairly high from the plant canopy to ensure even lighting distribution and prevent large temperature differences. Using artificial lighting greatly increases the costs due to their high electricity requirement. Additionally the heat generated by the lights needs to be cooled and disposed of in some way to prevent leaf burning or a suboptimal climate (leaf burning is especially important to consider in a vertical system since the plant density should be as high as possible per volume of space, i.e. the lights as close to the plants as possible). Proper cooling of the LEDs can slow down degradation up to 3 times (derived from Everlight LM-80 report). This can greatly reduce cost in the long run since lighting is one the most costly part of the climate-cell. Phillips is a large and trusted manufacturer of horticultural lighting systems and has a variety of models tailored to specific needs of plants.

Figure 21: LED light (‘Greenpower LED toplighting system—Philips Lighting’, 2019)

Normally the LEDs are turned on and of to simulate day and night. The cycles differ depending on the needs of the plant, like 16 hours day and 8 hour night. There is an argument to be made for implementing day light ‘chambers’ in order reduce the initial amount of LEDs needed and staying up to date on energy efficiency. In such a system the plants would move from a day chamber to a night chamber in order to conform to a 24 hour cycle. Since the lights would be used for 24 hours only 2/3 of the system requires lighting. However since the LED lifetime remains equal, they have to be replaced more often thus negating the investment savings. Energy savings acquired by switching to more efficient models more quickly could be beneficial, but this has to be compared to the additional installation cost, the cost of moving plants to a day night chamber and will most likely increase waste. Since the improvement of LED efficacy has a theoretical limit which research is well on their way to (‘U.S. Energy Dept. Environmental Impact of Lighting | DigiKey’, 2012) and additional systems could easily become more expensive the day/night chambers will only be considered if there are little to no additional costs for its integration. Extending the longevity of the LED is assumed to be a more effective costs saver since a temperature change from 65 to 45 degrees could increase the lifespan by around 40% (Cree Inc., 2009; OSRAM, 2018).

Water filtration

A water filtration system is required to prevent waste from building up like algae or plant roots that could clog the system. Next to that the water is sometimes sterilized using a UV light, but this requires numerous safety measures.

Sensors

Different sensors are used to keep the climate within the cell to the correct values, but can also be used to gather additional data not directly related to climate control. Typically used sensors are: pH, humidity, CO_2, temperature water, temperature air, lighting spectrum and/or a (infrared) camera.

Control unit

A computer or control unit is used to manage all electronics inside the greenhouse. Can be set to different climate settings, lighting patterns react to changes in weather all controlled via the main computer.

2.5 Automation and vertical systems

This part discusses the different ways in which automation and vertical farming has been or could be integrated in horticulture. Below (see figure 22) a collage is shown of different points of interest regarding the automation and vertical systems. The exploration of the current systems applied can provide insights for the development of different concepts later on. Similarly, different sectors where automation and or vertical structures are used, like warehouses, can be used as a source inspiration.

Figure 22: Collage automation and vertical systems

2.5.1 Automated cultivation and transport

Commercial viability is partly attainable with the reduction of costs through a reduction in labour. Automation and transportation systems are key elements for labour reduction. In this report automation is regarded as a system, or part of a system, working by itself without the need of a worker. Automation can reduce labour by doing a task previously done be humans. Transport of crops is another effective method to reduce labour, this can lead to an increase of speeds of up to 25% in strawberry production (Hendrix, 2006). In commercial cultivation this is achieved by transporting the plants to and from the worker. Automation and transportation is already a big part of some horticultural operations. Here various examples are given that show how these methods are currently being used and the possible cost savings are explained.

Automation and transport in cultivation

A good example of labour reduction in terms of both automation and transportation can be found in the production of lettuce herbs and other greens (Morgan, 2018). The automated part of lettuce production regards things like seeding (a machine placing lettuce seeds in substrates) and spacing of lettuce. Transportation of lettuce panels or gutters means the worker can stay at a fixed place while ‘harvesting’ the fresh crops. This relative movement speeds up the harvesting process since workers do no have to walk in between the crops. The lettuce plants go through several stages or baths. In every stage the plants are set further apart to save space. Stages comprise of long water filled bins where the lettuce gutters enter at one side and slowly move to the other end (see figure 23). At the end they are harvested by separating the roots from the crop. Note that automating lettuce production is far easier than automating fruity vegetables, since they can be harvested in one ‘swipe’ and do not require any upkeep. Compare this to tomato harvesting, where leafs need to be cut, canes need to be wired and lowered and individual fruits need to be picked, and automation becomes a whole lot more difficult.

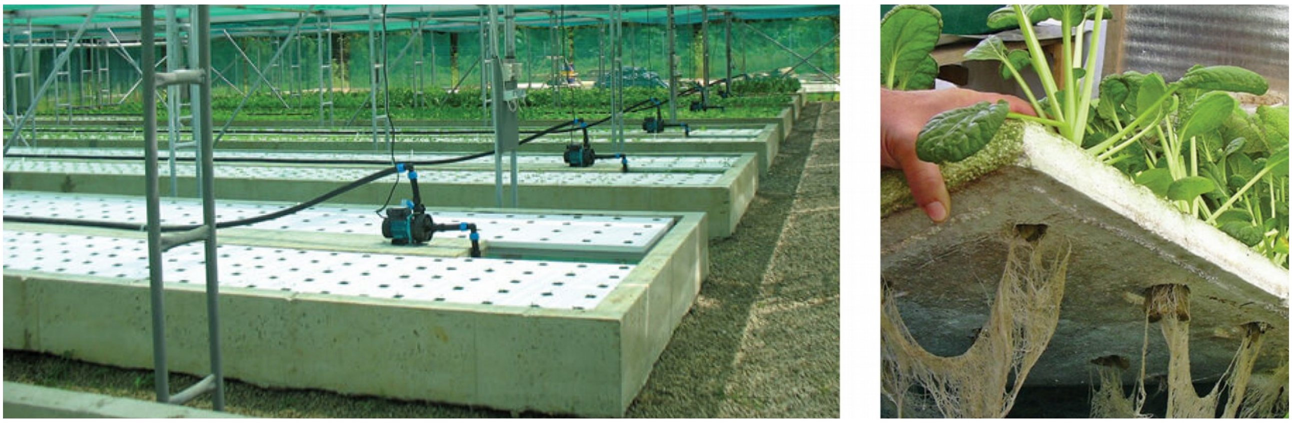

Figure 23: Production of leafy greens in DWC basins (Morgan, 2018)

More complex implementation of automatisation and transport by means of robotics has also been developed. Like the paprika harvester in Wageningen University (see figure 25). The strawberry harvester from Agrobot (see figure 24). These technologies allow for the harvesting of fruits and vegetables, but are still in development or not suitable for vertical production. A strawberry harvester from Agrobot already has an implemented picker suitable for open field and gutter harvesting.

Figure 24: Agrobot strawberry harvester (Agrobot, 2019)

Figure 25: WUR Block pepper harvester (WUR, 2018)

A careful consideration between mechanical and ‘smart’ automation technology is also needed to prevent overcomplicated of these machines or systems. For instance, the development of a failure proof fruit cutter could be less complex and more valuable than software that makes safely uses traditional cutters.

A good example of this over complication is the automated harvesting of blueberries and raspberries. In Norway an autonomous robotic arm is being developed which picks the berries one by one (‘Noorse robotexpert ontwikkelt robot die frambozen plukt’, 2019) taking around 15 seconds per berry (versus a few with a human worker), however a company called Oxbo International has long been manufacturer of a mechanical blue- and raspberry harvesters which ‘brushes’ off the berries mechanically (Oxbo International, 2019). The Oxbo machines harvests hundreds of berries a minute (see figure 26), far outplaying the robotic arm (see figure 27). This begs the question why such a robotic arm is being developed, if only for a more delicate touch. Most likely the quick harvester is used for frozen or to-be-processed industries and the individual picker for the fresh markets. For the fresh fruit market a shaking device such as the one from Oxbo could make the fruits less attractive or even damaged, though Oxbo states this is not the case. As of now no mechanical strawberry harvester has been made, likely due the possible damage imposed onto their soft and fragile body. Perhaps the smarter or quicker way would be to make the plant even more suitable for the harvesting method.

Figure 26: Oxbo berry harvester (Oxbo International, 2019)

Figure 27: Robotic berry picker (‘Noorse robotexpert ontwikkelt robot die frambozen plukt’, 2019)

Other sectors like distribution centres have long made use of automated transport systems and can provide inspiring technologies. This can be seen in promotion videos from companies like amazon where a lot of packages are moving throughout an entire system at high density.

An important remark has to be made regarding the transport of things like plants, gutters, etc. inside the system. The internal transportation is not only necessary due to a more efficient usage of space, but also about the expected decrease of labourer availability. If in the near future robotic harvesting is required and implemented, one should wonder whether the transport of things towards a robotic picking station is more efficient than making the robot pick on location, since this does not require the whole internal transport system and could be more space efficient. Transportation of crops should therefore be implemented in such a manner which does not do so for the sole reason of increased labour speed but also as a means of saving space.

Additionally, the transportation provides a solution to the current inaccuracy of automated pickers. Which according to the company Octonion, who developed a strawberry picking robot, differs per cultivar at a picking efficiency around 50-90%. The solution being a collaboration between the robot and human labourer. In this solution, the robot picks part of the fruits during the night for example and the human worker pick the remaining undetected or unreachable fruits during the day. In this way the workers can be slowly phased out with the improvement of the robot. However, it will likely be many years until full automation of strawberries of other crops can be realised.

Labour cost reduction

The costs savings automation can provide is rather easily determined. First calculate the costs of labour per kg produce using hourly wage and picking speed (this is the initial normal labour costs). Next, estimate the costs reduction given the increase in picking speed (this is the improved labour costs). The difference between these two is the maximum cost of an internal transportation system. When going completely autonomous the picking costs of the robot (given a certain depreciation) should be compared to either one of these two labour costs, figure 28 provides the estimated costs of a normal and sped up labourer for a 1 hectare strawberry farm. An overview on the calculation parameters can be found in the appendix Calculations Labour cost.

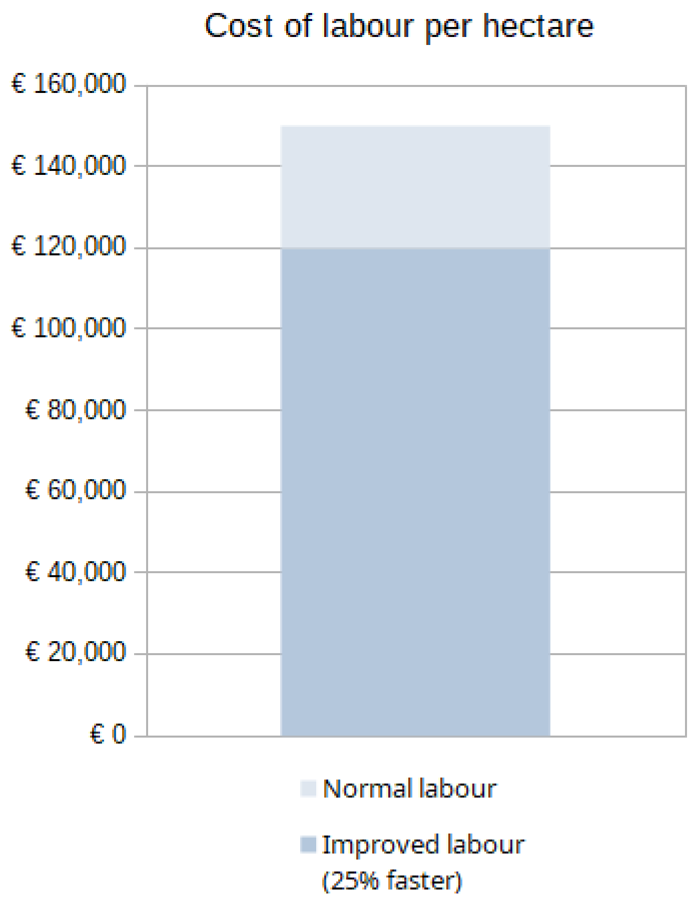

Figure 28: Cost of normal labourer per hectare versus 25% faster labourer in one hectare strawberry production (derived from Certhon data)

2.5.2 Vertical farms

Vertical growing enables a higher production per area of land which can be beneficial if the cost of land and or structure are high. Today the vertical systems are mainly used for crops that do not require a lot of lighting and upkeep like lettuce and not for crops that require frequent upkeep or harvest like strawberry.

Accessibility versus efficiency

The goal of vertical farming is to put as many plants as possible in a small space. A climate-cell is very expensive, so it needs to be used in an efficient manner. However, the problem that arises when simply filling a box with stacks of plants, is the lack of accessibility to the crops. Existing (vertical) farms overcome this problem by making pathways in between these stacks of plants (as seen in figure 22). However, these pathways create a lot of empty and wasted space and thus sacrifice plant density for accessibility. Figure 29 shows how much space could be potentially saved by removing the pathways between the gutters and stacking them 6 layers high (similar height as standard climate-cells). The design should not make use of pathways that take up precious/expensive space for the sole reason of accessing the plants. Even in existing vertical systems this could make the system twice as big. Instead it should only allow for the space according to the plant's needs (air circulation, lighting, irrigation), thereby making better use of the expensive climate-cell.

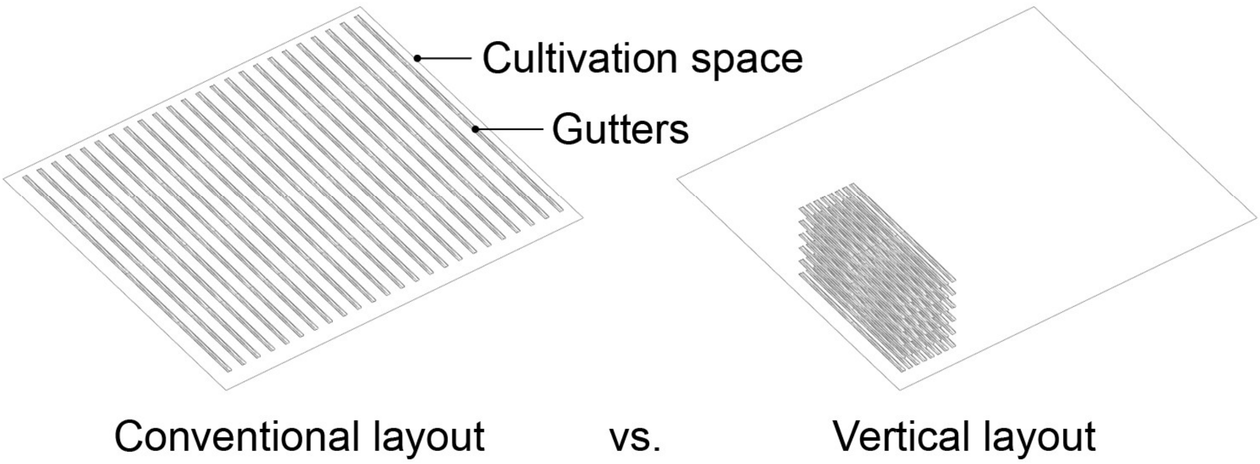

Figure 29: Conventional gutter layout versus compact vertical layout

Higher efficiency can be achieved in two ways. Either transporting the plants to a central location or adjusting the layout in a way in which the required space for the plant serves a second purpose and is not significantly bigger. Any design should make use of these principles and are thus further used in the ideation process (see 3.1.2 Morphological chart)

Since there will likely never be a 100% space efficient vertical farm due to the room required for the structure, transport, picking, etc. the goal is to make the growing volume at least 90% efficient. Meaning the volume of the climate-cell is filled for 90% with the components needed for plant cultivation and the remaining 10% is transport and upkeep. However, since space efficiency is directly related to scale (i.e. the bigger facilities have a relatively smaller central hallway) this requirement should hold true for a cultivation space of at least 0.5 hectare or more.

The vertical space between the stacks of plants also needs to be as short as possible, since this also improves the vertical space usage as well. This will be explained in chapter 3.2.1 Compacting the vertical structure .

Amount of layers versus structural costs

Aside from the accessibility problem there is a structural factor than limits the height of the final design. Namely, the building should be able to carry all the layers. More layers improves the space efficiency, but increases the weight of the system which requires a stronger structure (and is thus more expensive). Balancing precisely between space usage and costs of the layers is needed to get the most out of the available space in the climate-cell while keeping costs low.

There will be an optimal amount of layers depending on the costs of each additional layer. It is therefore important to know what this number is. However, this depends on the costs of the structure that holds all the layers, which is not known. Therefore a costs calculation has been made which plots several ‘cases’ to serve as a reference for finding the optimal number of layers using gutters as the substrate holder. The cases are calculated using the (simplified) formula below (see figure 30). The reason for using gutters in this calculation is their likelihood to be used in a commercial strawberry cultivation system (as explained in Substrates).

$$Cost(€/m) = \frac{Cost\ of\ climate\ cell + Cost\ of\ gutters}{Gutter\ length}$$

Figure 30: Layer cost calculation

The layer costs calculation is expressed in cost €/m gutter, because that defines the amount of plants in the system and thus the investment costs per production volume. It is also easily compared to other horticultural systems since prices in the horticultural sector are often stated in €/m or €/m^2. The “Gutter length” is the amount of gutters per meter times the amount of layers. The “Cost of gutters” is a variable that depends on the additional expenses of the structure that supports the gutters and is calculated according to figure 31. Where ‘n’ is the amount of layers and ‘x’ the additional cost factor (expressed in percentage).

$$Cost\ of\ gutters = \sum_{i=1}^{n} Cost\ of\ all\ gutter\ components * x^i$$

Figure 31: Cost of gutters calculation

Using the aforementioned formulas, a graph is made plotting the costs per meter gutter versus the amount of layers. In figure 32 this graph is shown for three different ‘cases’, indicating the difference between a 10%, 20% and 30% increase of costs per additional layer.

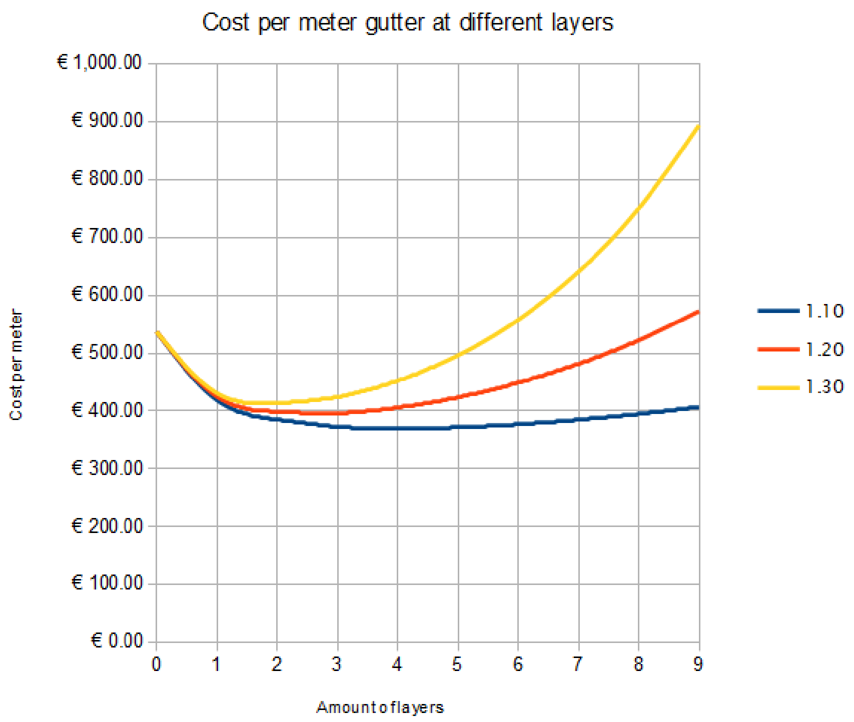

Figure 32: Cost per meter gutter at various layers for different additional cost percentages

When the costs for one extra gutter above the first gutter is only 10% more expensive (blue line) than the costs necessary for the first gutter (and so on for each additional gutter) then the total costs per gutter drops from around €550,- per gutter to only €400,- per gutter with only two layers. This drop in price comes from a more efficient usage of the climate-cell space.

For a 20% increase per additional layer this means the optimal amount of additional layers is 3. Additional layers only become more expensive than the initial cost per meter gutter after 10 layers. Note that here only the costs of the climate-cell is used and not the land value, so costs are likely even lower than indicated. Also, the climate-cell cost explained in 2.2 Running and investment costs are higher, since for the graph only the cost for irrigation, LEDs, plants, sandwich panels and the structure are used (these are the most interesting and relevant). The details for the graph can be found in the appendix Calculations Vertical layers.

Layer cost example

The graph in figure 32 is used as a reference to see how many layers should be build in regards to the cost per layer. One specific type of structure came to mind often used for storage at multiple layers, namely pallet racks. What makes these type of structures interesting is that they are optimized on price and weight capacity and could thus also be perfectly fit for vertical farming. Also, pallet rack scaffolding is used in warehouses for storing pallets at a high density. Sometimes the scaffolding is even used to support the structure itself, which makes them even more interesting to use. Finding the structural costs per gutter when using such an optimised storage solution can indicate whether going vertical could be as cost effective as the graph of figure 32 suggests. If the cost of the structure is far more expensive, one should consider that vertical cultivation is just not viable.

However, when using the prices provided by an online retailer (Begra Magazijninrichting BV, 2019) it would actually come down to around €7,- per layer and would be thus fall below the 10% percentage scale. Meaning the number of recommended additional layers is around 4 for optimal pricing (5 total when including the ground space). More detailed information about these calculations can be found in appendix 5.10.5 Pallet rack structure. Additionally, since the capacity of the pallet racks is not reached before the gutter suspension limit is (gutters have to be supported every 4-5 meters), there can be further costs savings.

One could also make make use of structural pallet racks, which are specifically designed to also support the roof of a warehouse and thus save costs and space for supporting the roof. It would require close integration of the cultivation system with the structural pallet racks. Another improvement could be to use only one support beam per layer instead of two, almost doubling the amount of layers without adding cost. However this might make the structure less stable or prone to buckling (due to the increased length of the upright) and should therefore be calculated first. There is still room to create an even better suited structural design for the vertical layers, which should be thought through. However, the use of pallet racking structures is considered to be an economically viable method of layered gutter support.

2.6 Requirements

As a result from the background and project goal 5 main requirements are set. These 5 requirements stem from the two essential needs of this project. Proper cultivation of crops requires both a suitable environment (1) and maintenance (5). While commercial scale facilities require a significant cost reduction at the most significant aspects (2,3 and 4). The main requirements are as follows:

1. Suitable for strawberry production indoors

   A suitable facility for indoor strawberry production regards roughly the use artificial LED lighting, nutrient supply by irrigation, ventilation and the access to the plants every other day for harvesting during the fruit-bearing period.

2. 90% plant space usage efficiency (m^3)

   Being highly efficient with the space usage of the climate-cell reduces the relative investment cost per plants. With more plants in the same space, facilities can become smaller while retaining their production capacity thereby avoiding additional land area costs and sandwich-panel cladding. Since space efficiency improves with scale this requirement should be met starting from 1.6 hectare size facilities which is the average size of greenhouse strawberry production in The Netherlands (CBS, 2017).

3. 85% direct light on plants when mature

   LED lighting electricity costs take up roughly 75% of the electricity consumption, therefore the light that is produced should be most efficiently used and preferably directly hit the crops for mos efficient usage.

4. Reduced or eliminated labour

   Labourers both add to the cost of the production process while declining in availability, Therefore the employees should either be able to work more efficiently or should not be necessary at all. However, this reduction or elimination should happen in a cost effective manner meaning the cost for speeding up the labour should not exceed the actual cost savings.

5. Opportunity for upkeep and maintenance of parts

   Any process is prone to failure or requires maintenance, therefore the system should allow for proper accessibility to components that likely require it.

Further detailing specific parts of these main requirements leads to an extensive list about the many components in the system like the specific dimensioning of irrigation or the replacement rate of artificial lighting. However, due to the many specific requirements related the design only the main requirements were mentioned here. The complete list of requirements can be found in the appendix 5.7 Detailed requirements. The appendix requirements state specifically what the company needs and wants are, what is needed for indoor cultivation and what requirements the final concept needs to comply to.

2.7 Wishes

Aside from the requirements there are aspects of the design which are preferred but not essential. These are the wishes. Since all requirements have to be met by the concepts to be considered viable the wishes partly play a role in determining which of the concepts are most interesting. They serve as additional design elements and can contribute to evaluated scores for the concepts. Similarly to the requirements mentioned above, only the main wishes are mentioned and a more extensive list is presented in the appendix 5.8 Detailed wishes.

wishes:

1. Quick development into product by Certhon (1 years)

   Concepts are preferred to be simplistic in a manner which allows the company to quickly further develop it. However, it is regarded as a wish due to the unforeseeable nature of design. For example, concepts that are not perceived to be quickly developed are not necessarily discarded if deemed a worthwhile pursuit.

2. Conventional cultivation method

   Given that the system is intended for large scale commercial production the production method is preferably one that is known within the sector. Any new or unconventional methods are however not deemed unworthy but are assumed to require more development time to get right.

3. Suitable for multiple crops

   A system fit for cultivation of other crops is considered to be valuable but non essential. Although the focus of the design lies on a production facility for strawberry cultivation having a system that with only minor adjustments can also be used for the production of other crops is considered a valuable feature.

4. Allows for parallel integration of labour automation

   The usage of fully autonomous systems is still years away while there already exist systems with a picking efficiency ranging from 50%-90%. A system that allows for the parallel integration of both human labourers and automatic pickers can bridge the gap between full autonomous systems of the future while also suited for conventional human labourers.

5. Simplifies installation and improves part longevity

   Vertical and autonomous systems exists but add complexity and cost that do not positively affect the price. Therefore systems are preferred which both simplify the installation and are more durable to cut costs.

3 Design

The success of a commercially viable indoor farm relies heavily on the proper design. The core challenge is to maximise space usage and crop accessibility while minimizing cost and labour. Specifically for Certhon the goal is to build a transport system in which plants travel from a high density production site to a central harvesting and upkeep location at low cost for commercial implementation. Various methods and techniques are used to guide the development of such a system into a valuable and novel design for the company. Here the design methodologies used will be discussed together with their results.

3.1 Ideation

3.1.1 Brainstorm

During the initial phases of the design (discover and define) one cannot help but to question the processes observed that are seeming inefficient or even cumbersome. These questions about the process spark the initial thoughts and ideas that serve as the starting point of the ideation phase. While brainstorming, these thoughts and ideas are sketched out on paper to illustrate different working principles of indoor vertical automation. The end result of a brainstorm, which figure 33 shows an example of, is a rather chaotic but extensive collection of random ideas. Brainstorm pages are therefore further refined and developed using a morphological chart and combining different parts.

Similar pages we're worked on extensively throughout the design phase, shifting between reference videos, mechanical systems books and other inspiration sources. This method of working on paper allowed me to clearly and quickly communicate idea's to the company R&D members and initiate conversations on improvements, etc. In those discussions I explained my thought process during the creation of the sketches together with their working principle, allowing for feedback on all ideas (similar to the explanations provided below on figure 33).

Appendix 5.5 Brainstorm sketches shows all other the brainstorm pages. It proved to be a good method for putting most ideas on paper with regards to the quantity.

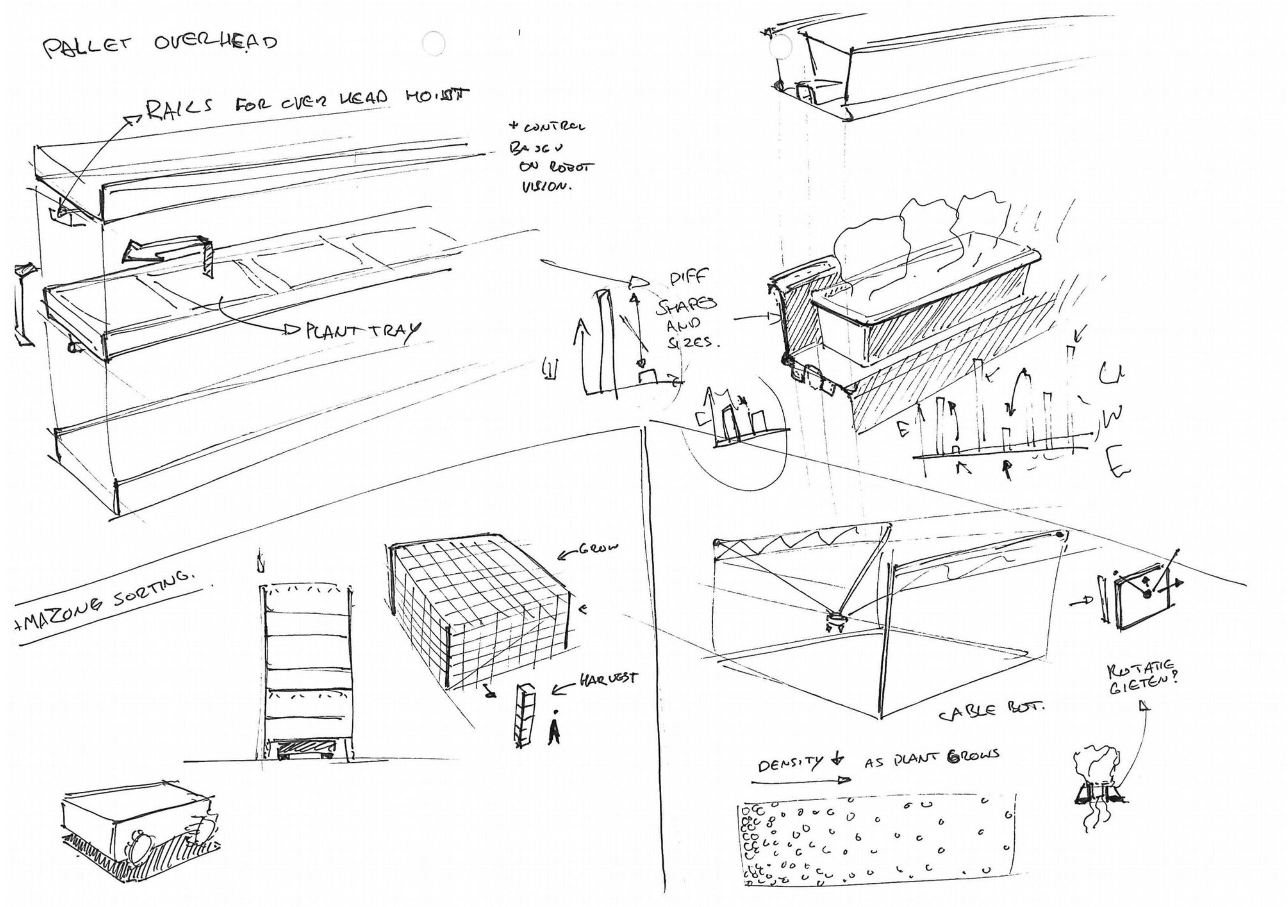

Figure 33: Example of brainstorm page showing 3 different ideas separated by lines

Brainstorm page description

Brainstorm pages like the one shown in figure 33 mostly contain multiple sketches about movement and structural packing for cultivation. The different idea's are often divided by lines on the paper so pages can be revisited without confusion about what belongs where.

In the upper left sketch one can see three layers with plant trays. The plants in this idea would be placed on trays during the growing period. Trays are then either picked up by a crane as a whole for harvesting or are harvested on location. The crane would ride on rails that are attached to the bottom of each layer. The upper right shows a different version of the same principle. Such a system could selectively take out panels with mature crops that are ready for harvest, however it requires sufficient space for plants to be moved above the other crops and a mechanism capable of doing so reliably.

The lower left shows a packing and picking method inspired by the amazon warehouse management systems ('Amazon Robotics', 2003). Small robots would go around the facility to pick-up a pillar of plants, then drive to a picking station and return the pillar to the growing grid after the fruits in the pillar are harvested. Using multiple transport robots the picking could happen continuously while keeping plant density at a maximum. This is a proven method to provide reasoning

The lower right shows a different method of picking and placing the plant from a densely packed growing location to an open picking location. This idea makes use of so called cable robots which have the benefit of being able to span long distances without requiring large constructions. The robot position is controlled via cable actuators. Such systems have been used to film field game matches for example.

3.1.2 Morphological chart

A morphological chart is used to showcase variations for features within the design in a clear manner. It usually comprises of a table with the first column filled with various features and a row of variations on executing that specific feature. For example, a vehicle can have a feature like steering and variations on how to steer like with a wheel, rudder, joystick, etc. Multiple variations (how ineffective they may seem) on a general feature can lead to combinations of features one would not have thought about before, which is great for generating novel and innovative designs.

For this project the most important and obvious features to generate variables for were: transport object (what to move) and transport medium (how to move it). Since these two features allow for high density growing while maintaining accessibility, i.e. by moving objects around additional temporary space can be created for things like upkeep and harvest. Other features included things like irrigation method, stacking structure, LED positioning, etc. which are also important to consider during the design (see 2.4.3 Climate-cell components). The list of features/variables of the morphological chart was partly expanded using “how-tos” that generated more abstracted principles of variations (see section How-tos).

In combination with the initial brainstorm sketches, a morphological chart can serve as a reference to alter parts of the design easily/quickly, hence the reason for using this method. And it can also spark the creative process when stuck or uninspired.

Transport item

Transportation is an important aspect of this project since the core problem lies within efficient space usage and accessibility. This project defines 4 types of transport items; transporting the whole system (plants, irrigation, lighting), the plant only, the fruit only and the labourer. Each of these different transport types has their advantages and shortcomings, e.g. transporting just the fruit or labourer induces less stress to the plant (since its stationary) but could become complicated with little space for movement, while transporting the entire plant or system could be mechanically intensive and expensive. Therefore, in the concept evaluation phase one concept of each transport category was chosen. Preferably the plant remains stationary to prevent added stresses to the plant during transport, but this stress is not considered to be detrimental to yield when keeping the speed lower than the maximum picking speed. However, in the future there might be a need to confirm the effect of movement on a plant.

An assumption is made in the design of the different transport concepts. Namely, the object which moves does not influence picking speed as long as the relative movement is equal, e.g. whether the plant moves in front of a person or vice versa does not change the potential increase in picking speed. However, when developing a system with robotic harvesting integrated the system does become more complex with regards to pathplanning if plants are moving relative to the base of the robots since the robot has to move continuously at the same speed of the transport while grabbing a fruit. Humans on the other hand are generally nimble and accurate enough to pick moving objects and thus do not suffer from this complication.

Transport medium

No matter what is moved where, its carrier has to be defined, since there is no transport without a vehicle. Especially in a vertical setup, the question becomes how do we collect the final product (berries, fruits, vegetables) from a certain height at a central location for outer transport to wholesalers and retailers.

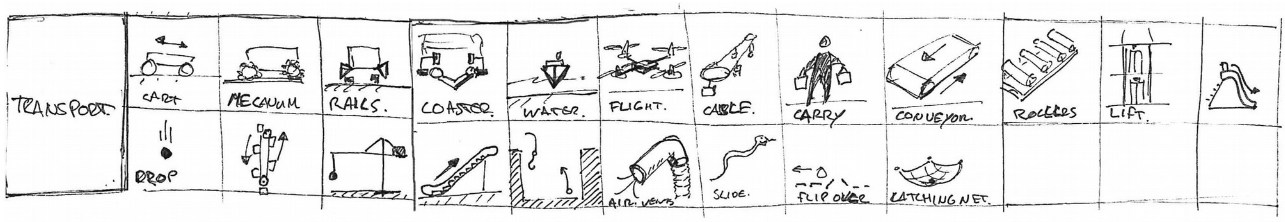

Figure 34: Transport variations for morphological chart

Combining transport medium together with the transport items already provides an enormous amount of possible combinations. Not all of these combinations have been sketched out, but as mentioned previously these categories allowed for clear iterations on the brainstorm sketches.

Take for example the upper left sketch from figure 33, if you change the transport medium from ‘rails’ to ‘water’ one can imagine the panels floating through those stacked rows from beginning to end. This, in combination with a gutter as the substrate holder, already provided part of the inspiration for one of the concepts (see 3.2.4 Plant transport).

3.1.3 How-tos

How-tos have been used to add additional morphological features and variations. Though distilled to their essence, more abstracted design principles separated from the subject matter can be generated with the goal to think outside of the box. The importance of generating inspirational how tos lies in the formulation of the questions without taking the subject matter into consideration. Instead of “How to put a room full of plants?” it becomes “How to fill a space?”. The latter question opens up far more possibilities that would otherwise not be regarded, one can fill a space with anything unbound by item, method or efficiency and thus be far more flexible in thinking of methods to do so.

A good example of this lies, again, in the transport medium variations. Instead of thinking about different transportation mediums as ‘transport’ e.g. “How to transport a plant?” the proper question becomes “How to move?”. This question if far broader and thus provides far more abstract yet general variations. Like an object simply falling from the sky is generally not considered transportation though something like ‘flight’ is. Yet falling from the sky can be linked to plant abscission (the plant letting go of leaves and fruits during stressful or low nutrient periods like autumn) which became an interesting long term concept (see 3.2.7 Abscission).

3.1.4 Reducing ideas to concepts

The methods used during the ideation phase led to an extensive pile of brainstorm sketches and morphological variations. This pile, though extensive and novel, is unorganized, crude and partly redundant. It thus had to be distilled into a concise yet detailed and realistic list of concepts considered to be most impactful and promising while retaining their variety and novelty. Without doing so, the work necessary to detail each sketch and/or idea would be insurmountable and in vain.

Ideas from the ideation phase were be partly merged together or scrapped by comparing different pages of (similar) ideas and using the feedback received from the company provided throughout the process. This first selection could then be further distilled into categories deemed most influential on the design like transport item and general requirements (at this point requirements are just used as a reference for keeping concepts viable). Finally, the ideas were converted to use a similar method of irrigation (NFT on gutters) so the concepts would (theoretically) have a similar plant density and light distribution. This allowed for a fair comparison between concepts, without creating bias for a concept simply because in a 3D model it looks like there are more plants.

NFT was set as the irrigation method since it requires less parts than, for example, drip irrigation while using less water than DWC, however from a cultivation point of view NFT is a slightly more complicated method according the Certhon agronomy personnel since optimal NFT cultivation techniques are not yet known. Gutters became the substrate carrier of choice since it only requires support every 4-5m which can cut down on installation and structure costs especially in the vertical direction (see 2.5.2 Vertical farms Layer cost example). However, the irrigation method and substrate carrier could be reconsidered if needed. This idea reduction process led to the concepts explained and detailed in the next chapter.

3.2 Concepts

As a result of the ideas generated during the ideation phase there emerged a selection of different concepts proposals deemed an improvement of the current system. Based on the core requirements (it should allow plants to grow and it is cheaper than conventional indoor systems) the following concepts are deemed sufficient for presenting to the company and detailing in the next phase. Concepts shown allow for the supply of all nutrients to the plants and their multi layered execution and compact positioning in the growing stage are more cost effective (though this is an estimation not ground in hard numbers given the stage of the project and concepts at this point).

3.2.1 Compacting the vertical structure

The first thing that needs to happen to the vertical structure is making it as compact as possible, producing more within the same space thus improving relative cost. In Certhon their facility especially, but also in already operational ones, I have not yet seen an integrated solution that truly combines components in a manner that maximises space efficiency.

I thus propose to integrate the various components into the gutter of the system. Where the LED is fixated directly on the bottom and the ventilation ducts are either integrated or removed completely using other means, like ventilating in the vertical direction instead of horizontally and parallel to the gutter.

Figure 35 shows how the system is already more compact by simply sliding and relocating different components. When stacking the gutters this effect accumulates in such a manner that more gutters can be place in the same place without compromising the space needed for the plant. Locating the air duct to the side is not regarded as problematic, since any crop requires room on the sides for ventilation and to prevent the plants from growing into each other.

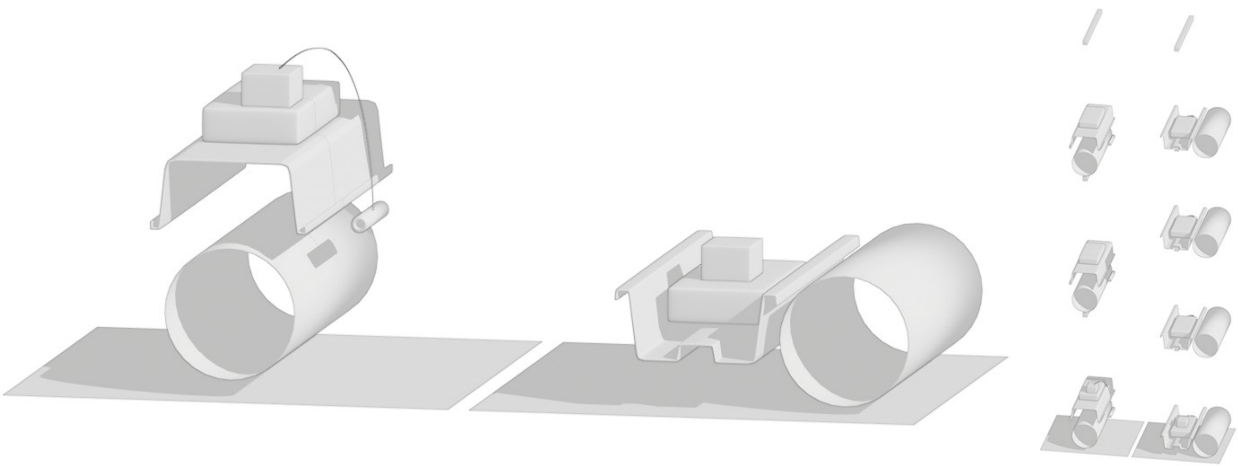

Figure 35: Vertical component integration comparison of current system (left) versus shifted (right) A stacked comparison is shown on the far right.

The additional benefit of placing the LED against the gutter is that the gutter can be used as a heat sink that transfers the heat to the irrigation water instead of using air to cool it or specially designed water cooled lighting. The available water already needs to be cooled due to the inefficiency of the pumps pushing it around which generates heat. Thus the cooling capacity of the system simply needs to increase. The benefit, as explained in the background, is an increase of the LED's useful life resulting in a lower investment costs while improving the indoor climate.

Removing the air duct from underneath the gutter by integrating it with the gutter or replacing it with some different ventilation method also simplifies the installation, since the gutter can be placed directly on a support beam.

Compacting the vertical structure leaves some issues to be figured out like how well the water cooling works, whether is it economically viable to use the gutter as an air duct, etc. These uncertainties are partly resolved in the part 3.4 Concept detailing. The integration of the different parts into the gutter could also work similarly for different substrate carriers like tables, however the general principle remains the same. Figure 36 shows different shape iterations for the integration of the airflow and water cooling into the gutter.

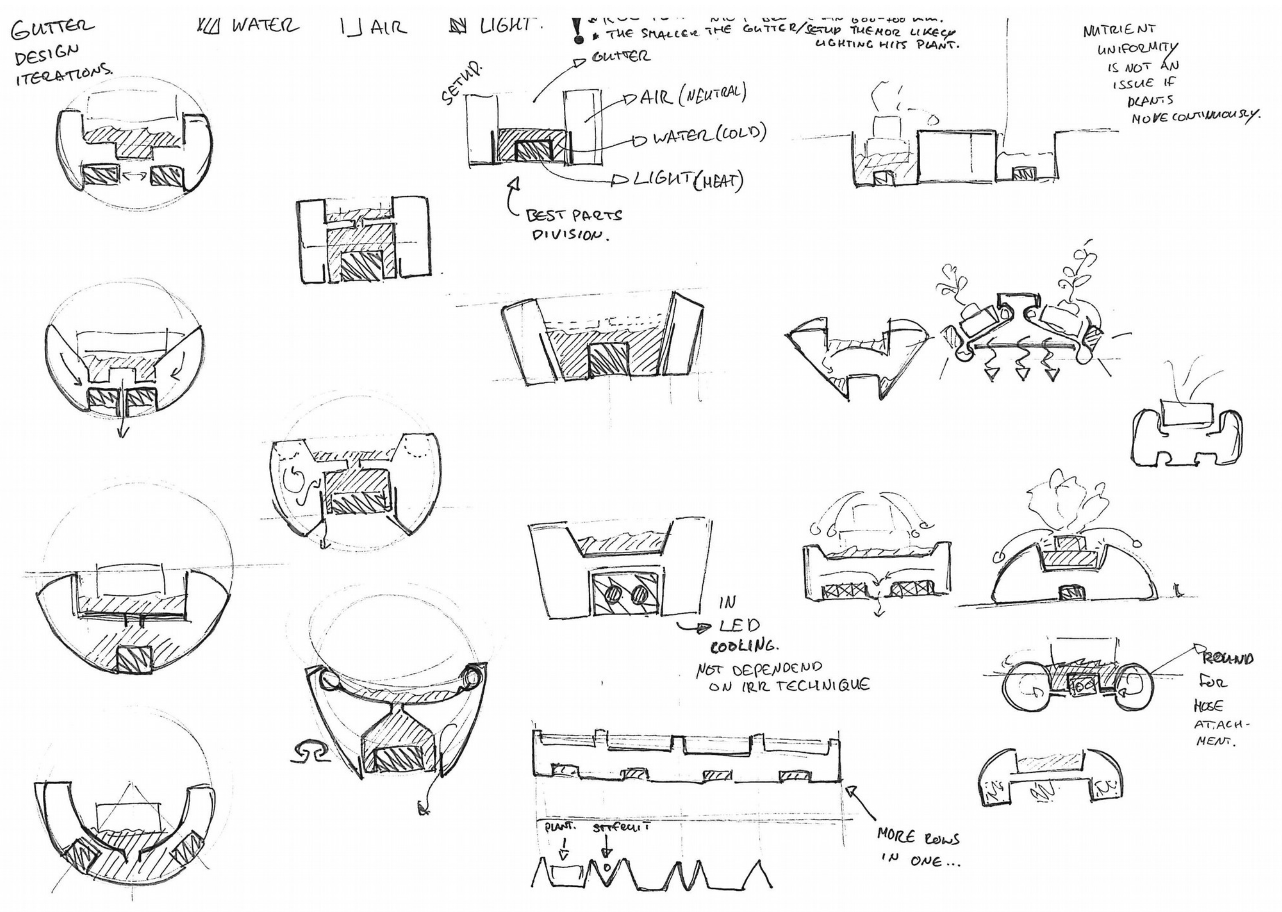

Figure 36: Gutter design shape and layout iterations

For the design it is important to create the most surface area of the LED with the gutter, have the water encapsulate the LED, have a large enough duct-size for the airflow, provide enough room for the plants to grow, etc. The concepts that follow integrate this proposal into the gutter. Meaning all concepts that use gutters integrate the LED light into the system with NFT cooling. However not all concepts allow for the air duct integration due to the gutter itself being moved which is therefore not shown. The LED and water supply are considered to be more easily integrated, due to the size of the components needed to facilitate them.

3.2.2 Gutter wall transport

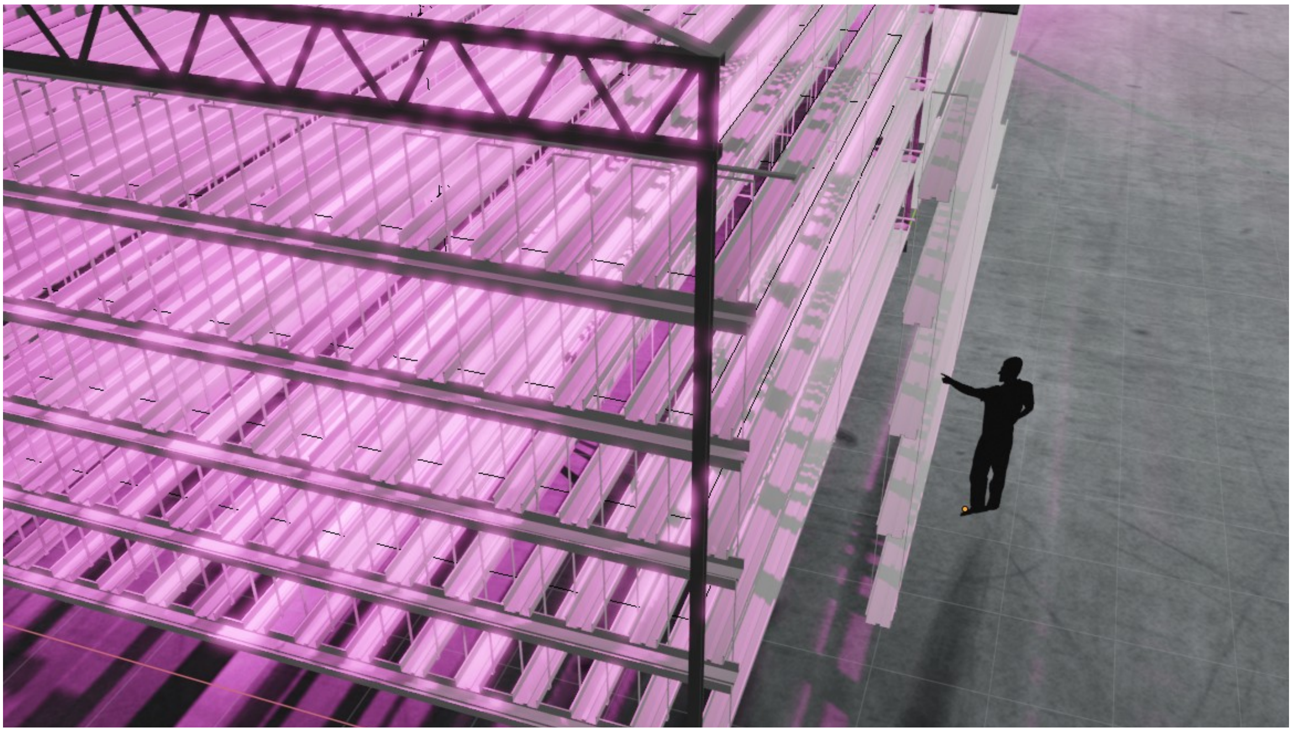

Figure 37: Gutter wall transport concept

Working principle

The gutter wall transport (see figure 37) allows an entire ‘wall’ of gutters to be transported to a picking station. These walls are placed right next to each other in multiple rows. The walls move like a train from the back of a row to the front. At the front of each row there is room for a worker to harvest the fruits from each gutter. After finishing harvesting a complete wall, the wall moves sideways to the adjacent row where it will move backwards, thus creating a loop where all gutters can be harvested easily while maintaining a high density growing capacity.

The gutters are stacked above each other and rest on a bend wire construction (see figure 38). Such a wire is regularly used in commercial settings to suspend gutters from the ceiling. The walls should be less wide than the beams that support the roof construction in order to move through them, though. There is a water inlet on one side and a drain on the other to cycle the nutrients.

Pros and cons

The advantages of such a transport are that an entire stack of gutters can be transported in one go (saving parts) and that the movement is relatively simple. A wall would move from the back of the farm to the front one by one. Once at the picking location at the front the wall moves sideways to enable stationary picking and to simultaneously move to the adjacent row which moves to the back to complete the cycle.

Some disadvantages are the amount of single and short gutters that need to be produced and positioned. Instead of producing gutters of +50m, these are only around 8m and can therefore not be produced as quickly. Also the construction of the system can become quite heavy and thus hard to move requiring heavy machinery and rollers that hold the weight.

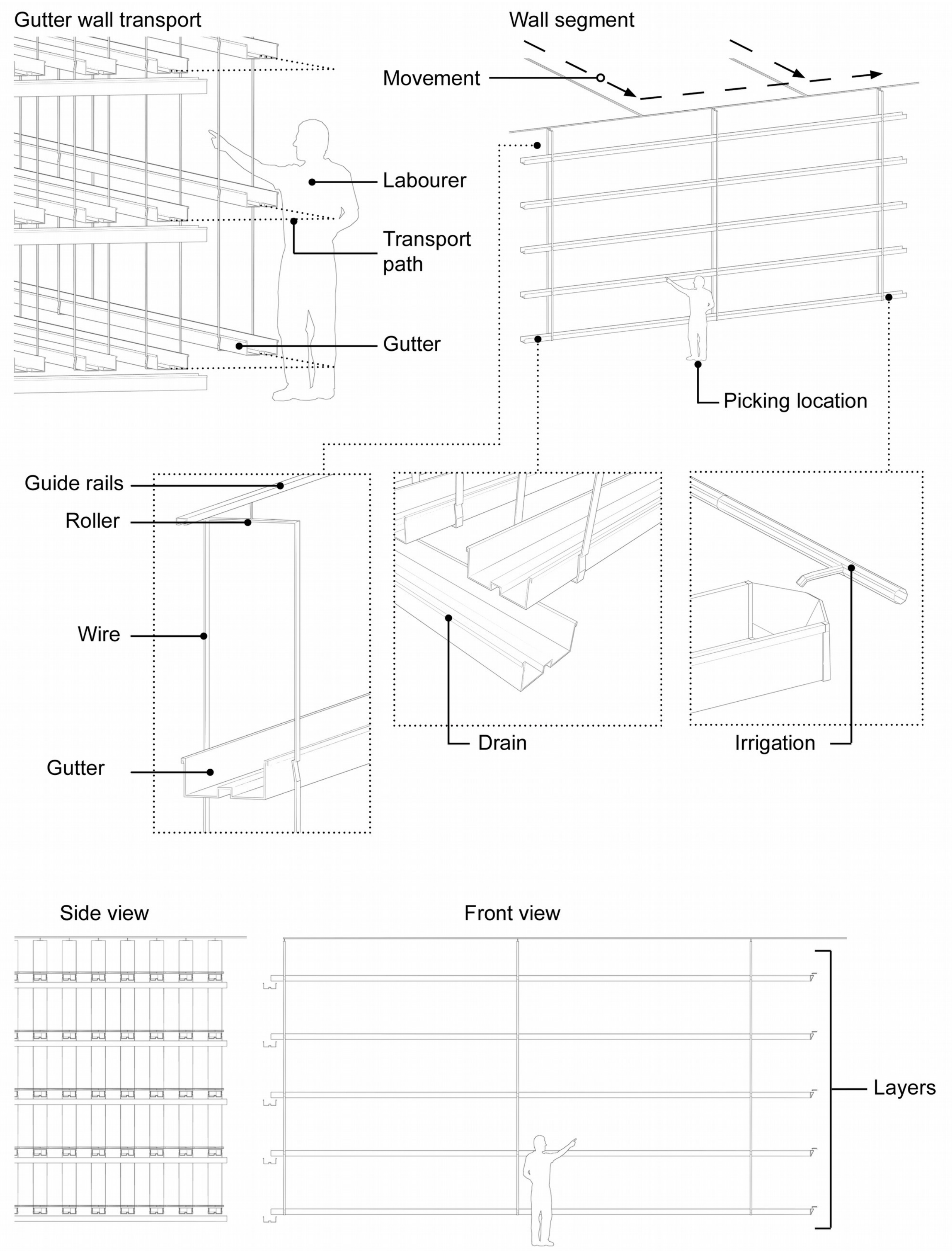

Figure 38: Wall transport details

3.2.3 Gutter transport

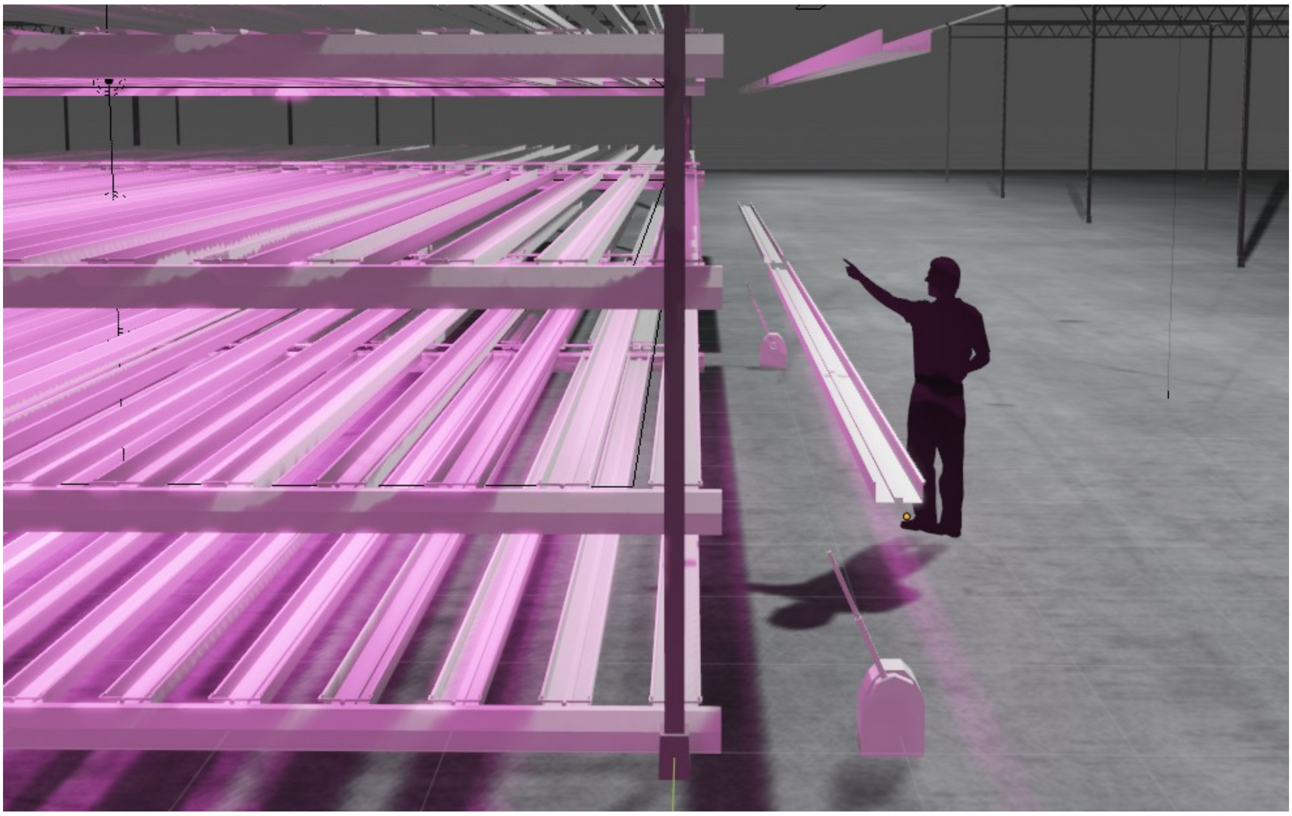

Figure 39: Gutter transport concept

Working principle

The gutter transport is derived from existing transport systems where single gutters are moved wich are filled with plants. However, this system is made to transport vertically as well. Here the gutters move from the back to the front and are lifted to the height of the layer above. After picking the gutter is placed in the new row. The gutter moves to the back and lowers again into the layer beneath to complete the cycle.

Each gutter in the system has two rollers on each side which rests on the drain serving as a guide rail (see figure 40). A mechanical arm is needed to grab each gutter and transport it to the different locations.

Pros and cons

The advantage of this system is its fewer picking locations. The gutter cycles between a bottom an upper row which halves the amount of vertical picking locations. Having fewer vertical picking locations provides more space around the picking stations which can simplify the process. Picking can also start from the ground since the gutter can be lifted to more ergonomic heights.

A similarly working conventional system is known to be too expensive, so there is a high chance this will be a similar case. Just like with the previous concept, there are a lot of moving parts which will wear out the system and requires replacement.

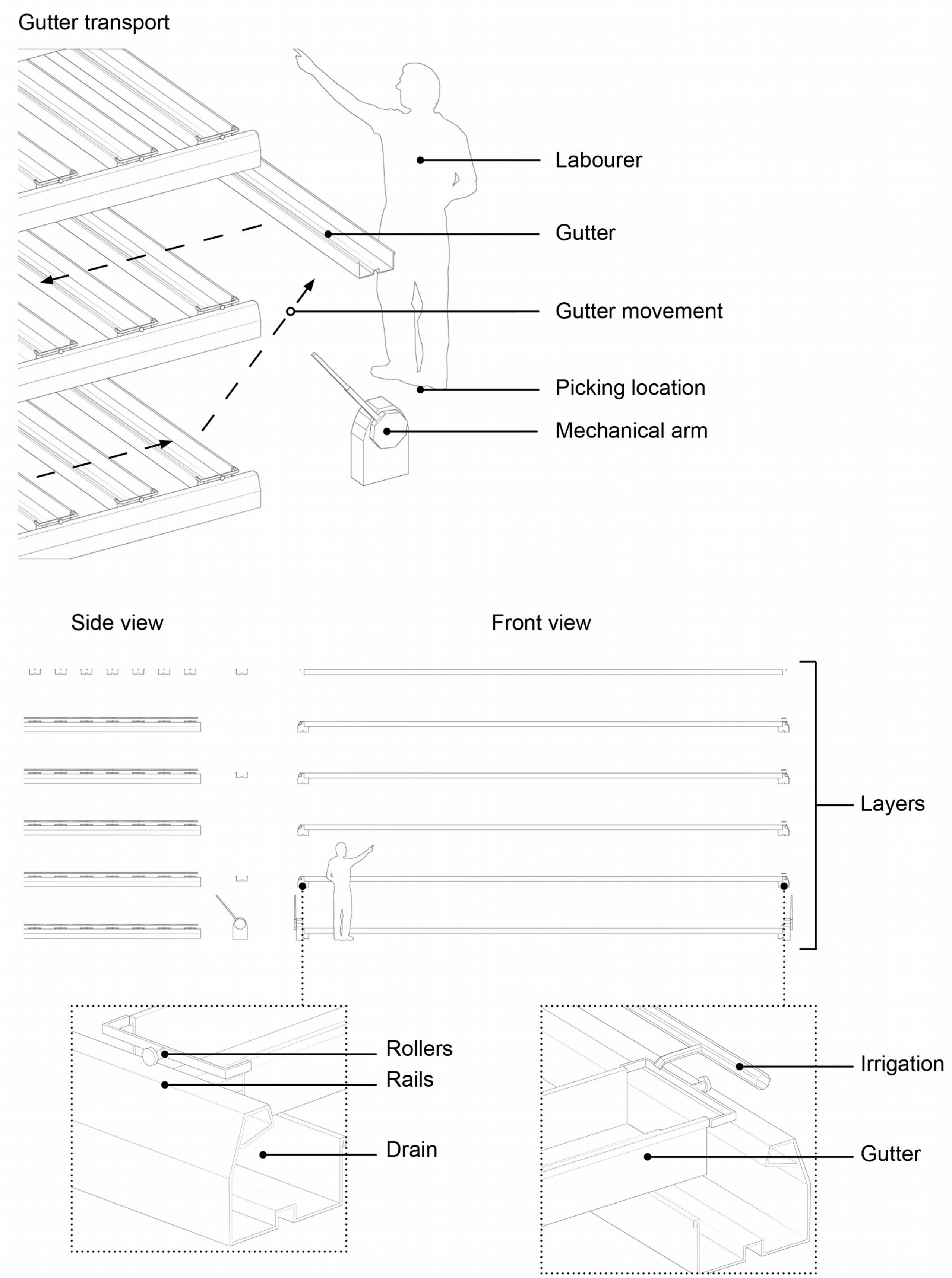

Figure 40: Gutter transport details

3.2.4 Plant transport

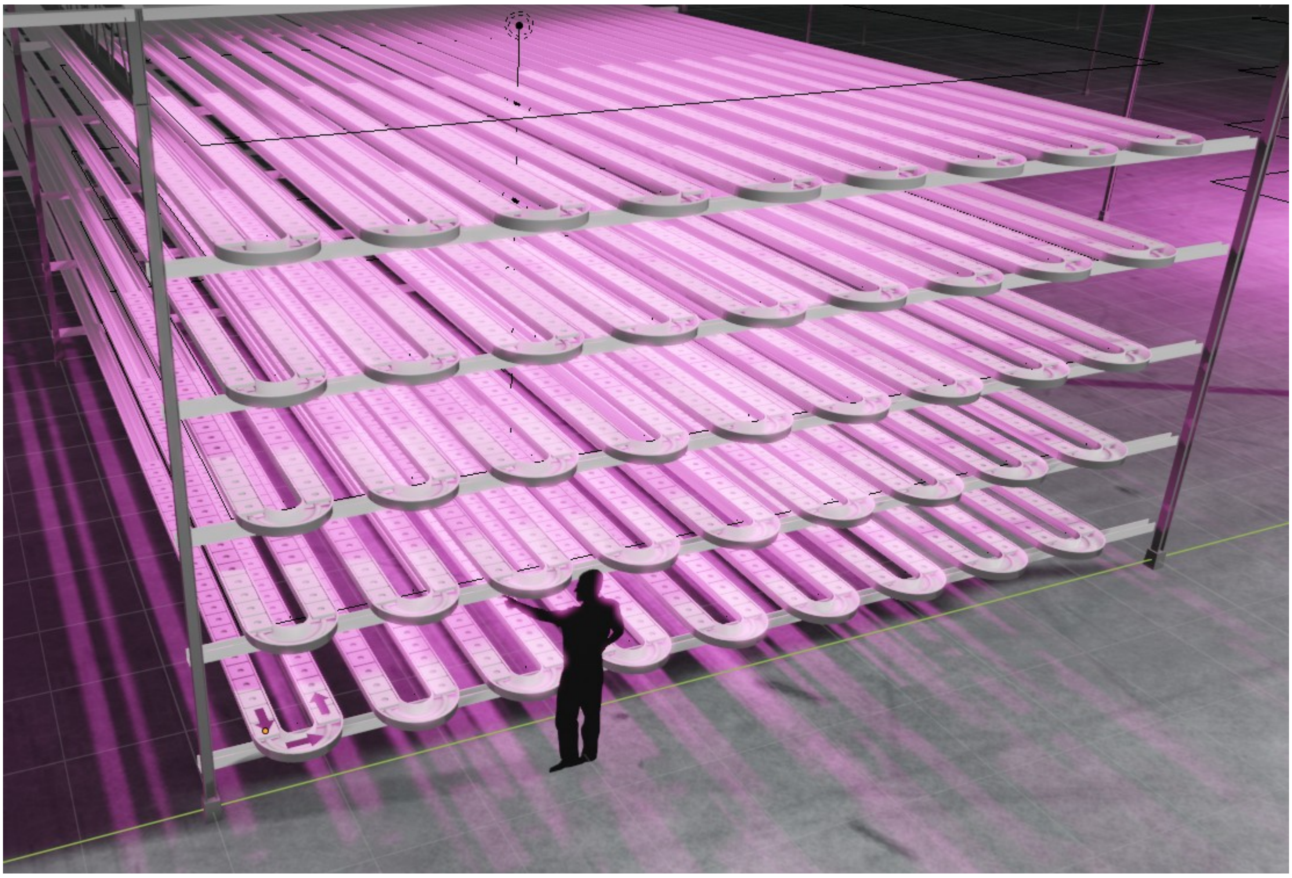

Figure 41: Plant transport concept

Working principle

In the plant transport (see figure 41), as the name suggests, only the plants are moved through the system. This happens using floating rafts. In this version the plants move from the back to the front along two adjacent gutters which are connected via a U-shaped piece (see figure 42). The gutters rest on beams and are stationary.

Pros cons

The advantage here is its minimal amount of moving and prone to wear parts compared to the previous concepts. Only the plants are transported using the water available in the gutter which is a very simple transport medium, often used in DWC setups. Unlike the previous two parts, the gutters can be any desirable length since they do not need to be cut to fit the transport system.

The downside of this concepts is its many picking locations and the need for the person to move to each individual one. Accessibility to the crop is also limited since the gutters are not able to move out of the way.

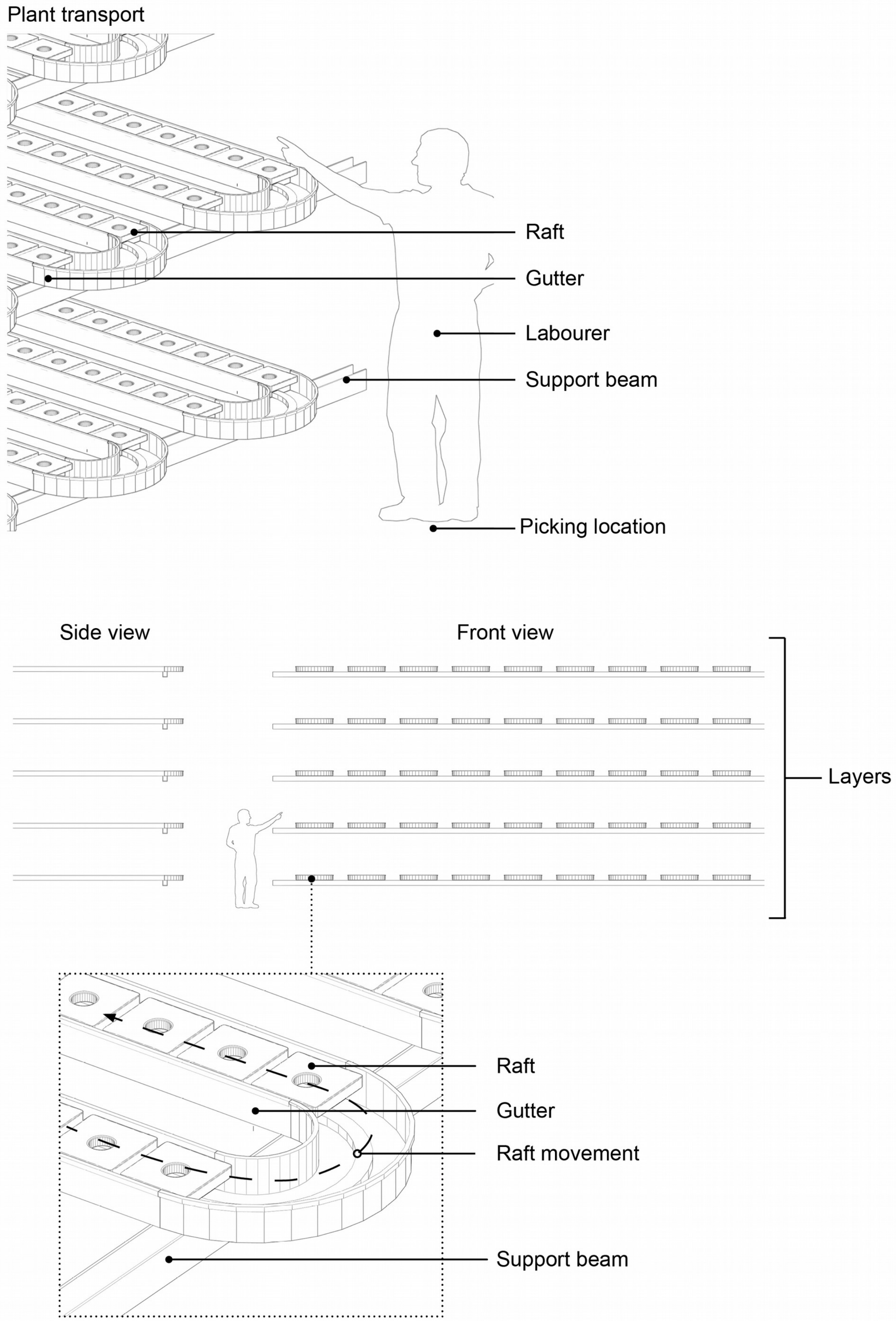

Figure 42: Plant transport component details

3.2.5 Plant Wall

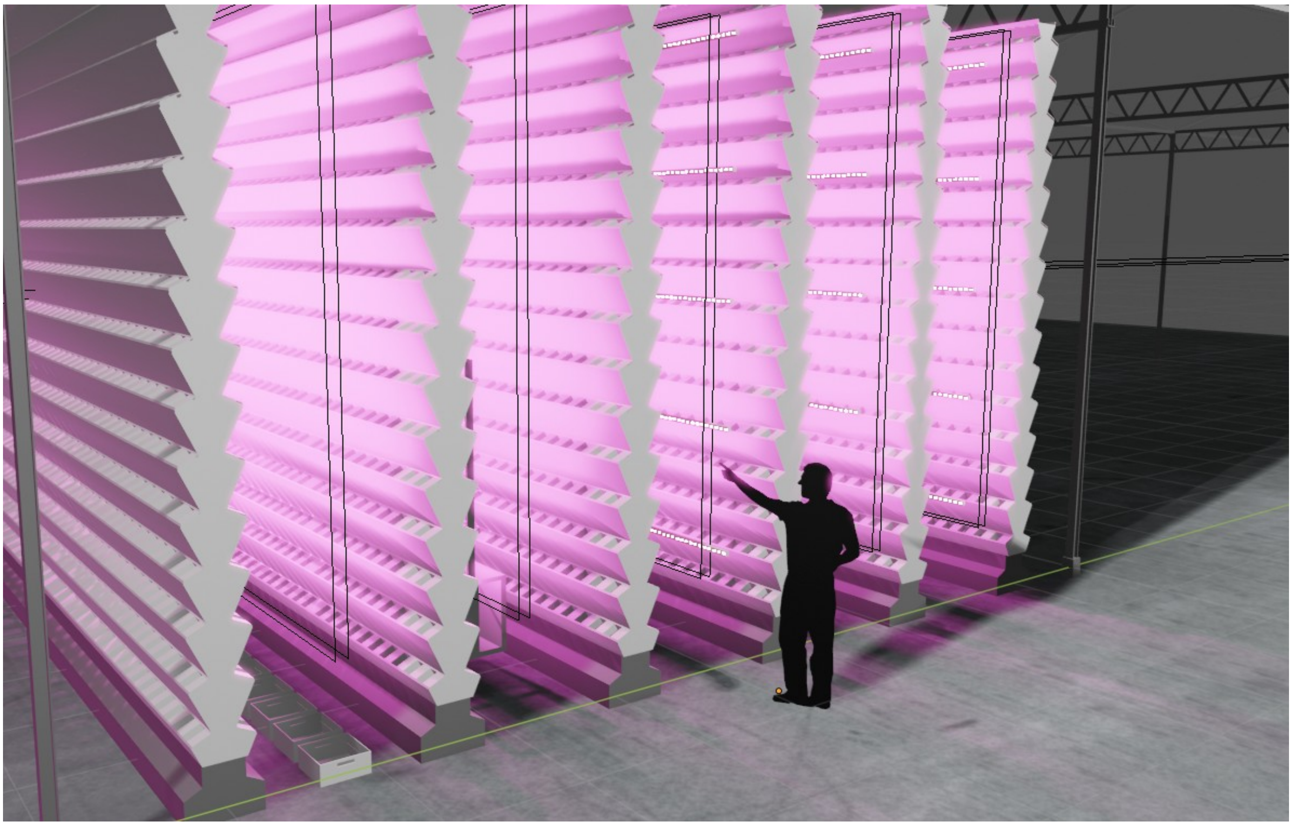

Figure 43: Plant wall concept

Working principle

The plant wall (see figure 43 and 44) provides a completely stationary growth area where the worker moves between two rows of crops facing each other. By facing the plants toward each other there emerges a larger space for people to walk in between, a space which is also necessary in horizontal growing planes but not combined. LEDs are suspended in the pathways between the crops during the lighting period. Once crops need to be harvested these lights are moved upward to provide room for the labourer. The labourer then makes use of a cart (to be further developed) in order to harvest the fruits of the entire wall.

Pros and cons

The lack of moving parts is an advantage in this system, since there is less wear on parts and no stress on the plants from movement. Rows can also be of an arbitrary length since it does not have to conform to a specific transport system like with the first two concepts. And, since picking happens on location, the accessibility to the crop is optimal.

A disadvantage of this system is its yet unproven productivity. No commercial growing is done is such a manner and shall thus first need to be proven viable. Aside from this there is a required additional safety factor when transporting people which need to be met (especially when working at a height). These include, but are not limited to, a maximum speed, protection against suspended parts from above and prevention of tilting over.

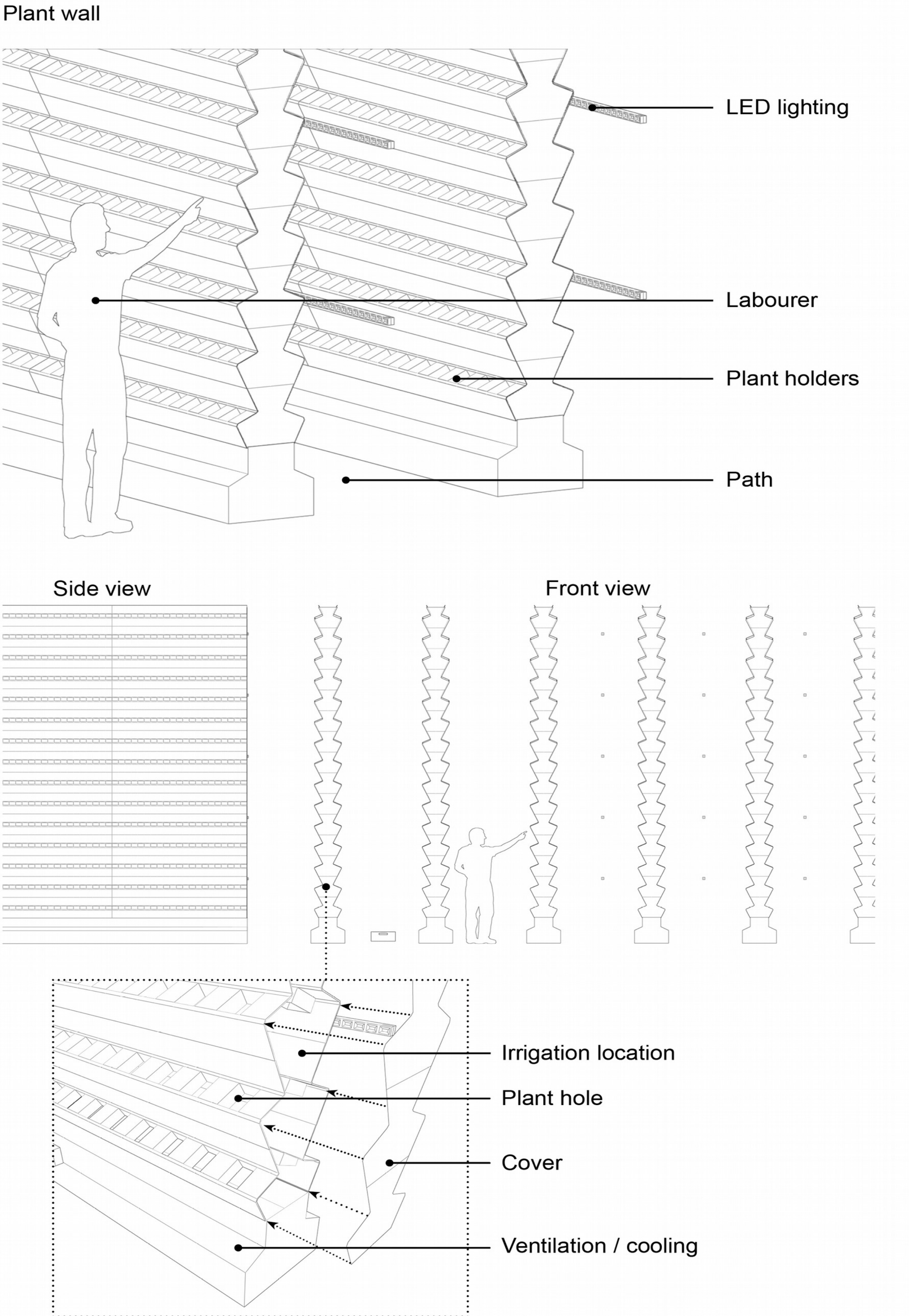

Figure 44: Plant wall details

3.2.6 Gutter rail bots

Figure 45: Gutter rail robot concept

Working principle

The gutter rails robot makes use of the gutter to transport itself along the rows of plants (see figure 45). As described in the background, the availability of labourers is declining and pushes the horticultural sector to automation. This concept, unlike other robotic methods, transports itself through the crops without the need to move the crop (aside from seeding and cleaning). It harvest between the crops by riding on the rails.

Pros and cons

This concept provides a method of working toward a fully autonomous system where perhaps 100% robotic upkeep might be achieved. Achieving 100% picking efficiency is not easily done and will likely require a lot of training data, however this method could be implemented on a commercial scale where that would not be an issue. Additionally when deploying such bots to move trough the system the space needed for plant growth might be enough for the robots, thus eliminating the need for moving plants to higher density areas.

The robot itself would need to be developed in collaboration with other parties, since Certhon cannot (yet) do so internally. It will be more expensive in the beginning when there is no fully autonomous system in place.

3.2.7 Abscission

Abscission is a biological process in which the plant detaches unneeded parts of its body, like letting go of leaves in autumn. Similarly a plant can let go of its fruit. This, currently happens once the fruit is overripe or if the plants do not have the strength to produce them. Just like how during winter the conditions are too harsh for most trees to have leaves. This concept falls back on the principle stated earlier in the report where the plant is designed to suit the system, here the plant is bred or designed in a way that it works in our favour. The principle of abscission could be a breed trait where the plants let go of their fruit once perfectly ripened (or when they are normally harvested) or with only a little shake of the plant. If a future strawberry plant naturally drops its fruit once perfectly ripe, the only part left to design is a system which catches and collects these falling fruits. There would be no need for complicated robotic pickers to replace human labourers or the transportation of plants to optimise space efficiency. There already exist similar harvesting methods that make use of this principle, only with a little help. Such systems make use of mechanical harvesters that shake off ripe fruit and have a collection basket that catches them.

Note that this concept is merely a thought experiment in which the principle of picking a plant suited for the system is most strongly apparent. Such a concept could be worked towards, since this would lead to an easy solution to the problem (no labour, no need for accessing the plants, etc.). However, this is not considered an industrial design related solution.

3.3 Concept evaluation

Evaluating and comparing the different concepts according the companies requirement is necessary to select a final concept with certainty on the direction and scope of this project (Concept detailing). At this stage all concepts were at a point where further detailing would require significantly more work, which would be in vain for those concepts not to the liking of the company. The concept evaluation was conducted in three phases, to get a both thorough and simple evaluation depending on the parties involved with the final decision.

First a list of evaluation points was made using weighed objectives, which provides a thorough evaluation method that could be filled in together with the company supervisor. His input for this evaluation was most valuable, since he was already well informed on the different workings of each concept and did not need a lot of further explanation. The weighted objectives served as a detailed assessment where the most important aspects and limitations of each design were covered.

The second phase was a group evaluation with the R&D members of Certhon where a preliminary concept decision was made in order to present a unanimous concept preference to the upper management of the company. In this evaluation the concepts were presented with their pros and cons, similar to the explanation of the concepts in the previous chapter.

The third phase was the evaluation of the concepts in a concept presentation with the upper management of the company. Using rough evaluation criteria that aligned closely with the wishes of Certhon and the pros and cons previously mentioned they could quickly be informed on the progress so far while forming their opinions on how to continue forward.

3.3.1 Weighted objectives Criteria

Weighted objectives criteria were used as an evaluation method due to the complexity and open nature of the previously mentioned concepts. For each criteria a weight is assigned depending its perceived importance. Per concept a score is given for each weight depending on how well it meets the criteria. Below the different criteria are shown. Further results can be seen in appendix 5.9.1 Weighted objectives.

1. Plant density and light density: both considered to be equal among all players, but of the biggest importance due to the high costs associated with them.
2. Development time: How quickly can Certhon fully develop and apply this concept.
3. Costs: how much room for investment is required compared to what costs it eliminates
4. Weight of moved parts: how much effort / complexity does the transport require
5. Accessibility: how well can the crops be reached in case of malfunction.
6. Installation simplification: Compared to conventional systems how much easier is the installation of the system.
7. Usability: how well can it be used/maintained and how much work does it alleviate
8. Plant knowledge: does it take any additional testing in terms how well the plant grows in the system

9. Safety: How many additional safety concerns arise with the implementation of the concept
10. Future implication: How well can this design be further developed into more valuable structures

The resulting scores were also given a certainty factor depending on how much could be evaluated with certainty. The weighted objectives provided a means to make an initial evaluation with less bias and more constructive thinking. Even though most concepts were rated differently, there was a fairly similar result with no clear winner. The plant wall scored best mainly due to its positive accessibility.

Due to the many uncertainties that remained in the different concepts no clear preference could be established. Therefore, during the concept presentations these results were not used. Instead the core insights for each concepts (pros cons) were used together with more general list of pros and cons as previously explained for every concept.

3.3.2 Company presentation criteria

During the concept presentation a concise list of criteria was established (matching with their requirements) in order to quickly communicate and compare the different components to the less involved upper management of Certhon. Figure 46, shows these criteria together with their rating for each concept.

	Plant transport	Rails bot	Plant wall	Gutter transport	Wall transport
Development time	Low	High	Medium	Medium	Medium
Cost	Low	Med - high	Low	High	Low
Flexibility	High	High	Low	Medium	Medium
Transport	Plant	Fruit	None	Gutter	Gutters

Figure 46: Concept presentation criteria overview

Development time is estimated to be the longest for the on rails picking robot since it is most technologically advanced and not within the capabilities of the company. The medium rating was given to those concepts which require some sort of mechanical movement, though there are differences in the complexity of the movement they compensate differently based on safety and tolerances required (a plant wall requires safety, the wall transport accuracy and the gutter transport both).

Cost are determined based on the complexity of the system and components required together with the potential cost it could eradicate (similar to point 3 of the weighted objectives). Here, plant transport, the plant wall and wall transport are rated low since there are very few or easily moved parts.

Flexibility regards the possibility to grow other plants without concerns or big changes to the system. Since the plant wall is a radically different method compared to conventional gutter production it is rated low. Both the plant transport and rails robot are conventional executions of the gutter with transportation build in and should therefore be not any different in flexibility from the conventional systems.

3.3.3 Decision

The plant transport concept was perceived by the company as most promising. This was due to various reasons. The companies ability to do further development without any additional external party played a key role in this decision. Also the simplicity of the mechanism and the flexibility of plant material were reasons for wanting to go further with this design.

The proposal to compact the vertical system by integrating different components (light and ventilation) was also well received and had to be worked on further to proof its viability. Mainly the costs of the ventilation duct in the gutter and the heat transfer to the water had to be proven worthwhile.

This decision set a clear scope for the remainder of the project. The remainder of the project could therefore be focussed on the detailing of the concept. In the concept detailing any concerns that remained at this point were either solved or removed from the design.

3.4 Concept detailing

In the concept detailing the proposed concept is further developed into a complete and viable proof of concept. Here the specific dimensions of the raft, gutter and frame is researched and defined. The end result is a complete proposal where shape, materialisation, working principle, etc. are explained or proved. With the help of prototyping, calculations and 3D modelling definite choices are made that contribute to the final design.

The plant transport gutter adds several functions to the conventional gutter. Namely; irrigation, ventilation, lighting, cooling, plant transport and maintenance. These features come from the requirement of making the vertical structure as small as possible and enabling the transport of plants (and thus fruits) to a central location for optimal usage of the climate-cell space.

All these features are favourable but need to be evaluated using real world test, simulations or calculations to confirm whether it is not just a good idea on paper. This part will thus discuss the different measures taken to see if and which design can work in large scale operations. The additional usage of nutrient water intake is tested to confirm the possibility of using it for both floating the rafts and cooling the LEDs. The order of execution happened as follows: explaining choice of irrigation, developing the rafts (shape and material), integrating the LEDs and calculating the required flow, checking the gutter air duct integration and finally defining the transport cycle to and from the central area. The main concern of this detailing phase is to confirm the proper working of the system and economic viability. A list of other concerns at this point are stated in the appendix (see appendix 5.9.2 Post concept decision considerations).

3.4.1 Irrigation choice

When irrigating crops on gutters often the choice is to use drip irrigation. This ensures every plant receives the same amount of nutrients while the water retaining feature of a substrate like rock-wool keeps the moisture inside. However with drip irrigation the plants are ‘stuck’ to the dripper which connect to the hoses and are not easily transported while the gutter has to carry the additional weight of the substrate slab. Instead, the intended method of irrigation is a combination between NFT and DWC (there is more water than conventional NFT and less than conventional DWC).

This slightly elevated NFT system has already been used by Certhon on stationary plants and proved to be a viable irrigation technique. The only problem with NFT and DWC is the fact that the nutrient water needs to be replenished every so often (becomes more frequent with less water volume), but it consists of a continuous stream of water which is preferable for the LED cooling. The importance here lies in both the speed of the water (at a too high water velocity the plant cannot take up any nutrients) and the nutrient uptake (at what speed the nutrients are consumed and need to be replenished). Since these aspect are highly dependent on the climate, plant and volume of water in the system the values for nutrient replenishment would be at least 2 times a week with a maximum water flow speed of 1 meter per second.

In order to keep the nutrient homogeneous, the gutter should have an inlet and outlet every other 5 meters (i.e. first and inlet, 5 meters further an outlet, 5 meters further an inlet again, and so forth). Precise data on specific water speed, volume nutrient uptake are not yet known and can thus not be defined. Later calculations shall also indicate that the plant nutrient supply will not be a limiting factor for the irrigation dimensioning.

3.4.2 Raft

The raft is the main component of the concept and should behave properly for the system to work as intended. Therefore the design and testing of the raft is prioritised above the design of the gutter. However, the design of the gutter is held in mind, like leaving space for the LED and maintaining enough room for the plant. The core requirement for the raft is its capacity to float while bearing the weight of at least 8 plants per meter. Additional requirements can be found under the ‘post concept decision’ requirements.

Raft design process

At first the general shapes of the raft is explored and a defined (see figure 47). These sketches from different viewpoints provide a clear overview of possible shapes and is used to create a variety of 3D raft shapes (see figure 48). These blocked shapes are also sketched in hollow form (see figure 49). These function as a reference for the raft design. The shapes of these sketches consider the following (not all present in each shape): flanges for the protection of fruits and leaves, cut-outs for the placement of plants in substrate blocks, a notch for the LED gutter integration, shape that closely follows the contour of the gutter, space for roots and a checker pattern for compact plant spacing.

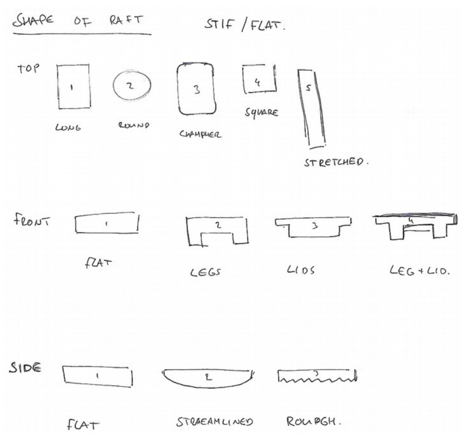

Figure 47: Raft shape variations at different viewpoints

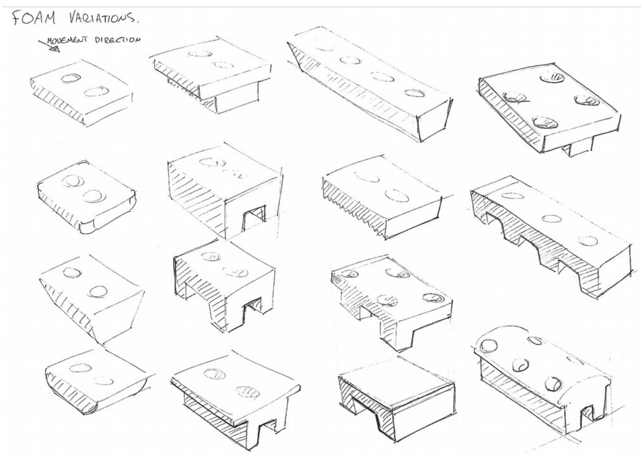

Figure 48: Blocked shapes for rafts from viewpoint variations

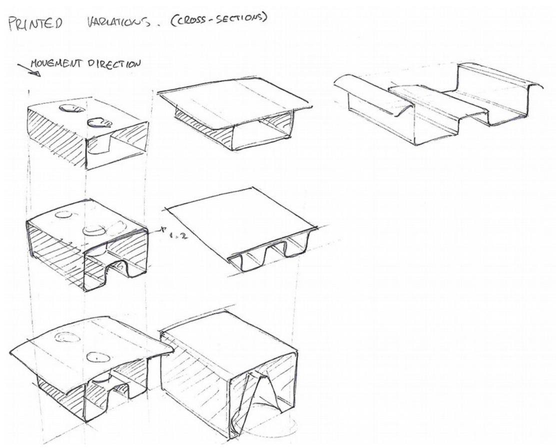

Figure 49: Hollow raft shape variations (cross-sections)

Since the rafts need to float they require sufficient buoyancy. The required buoyancy can easily be calculated given the maximum weight of the system. The weight of the system should be equal to the weight of the volume of water that is displaced by the raft, i.e. the buoyancy (figure 50) should be equal to or higher than the downward force. If for example a system weighs 1 kg, more than one 1kg of water (1L) needs to be displaced for it to float.

$$B = p_f V g$$

Figure 50: Buoyancy (B) formula,where p_f is the fluid density, V the volume and g the gravitational acceleration.

Excluding the raft weight, the raft should be able to float with 8 plants per meter (0.3kg per plant) and thus displace at least 1.6L in order to float. Since calculating the buoyancy is merely a theoretical confirmation, later on the final raft will be used to compare the expected buoyancy to the actual.

Other aspects like the force required to push the object when floating, if the raft could get stuck and the stability of the rafts (and other intended functions) are more easily figured out in a simple test setup. Therefore, some of the block shapes from figure 48 have been made into styrofoam boards to confirm the proper working of the concept (see figure 51).

Figure 51: Styrofoam raft test setup

This test setup showed that the rafts (as expected) could easily hold the weight of the plant given the design. It also requires very little pulling force (0.1N per meter) even when dragging on the surface of the gutter. This also implied there might be a possibility to (partially) transport the gutters with only a stream of water, but this is not considered yet. There were some issues with the instability (hence the reason for shapes with flanges) so flanges will serve the additional purpose of stabilising the raft (the other being preventing fruit damage from drag). The width of the gutter was far smaller in the test setup so the buoyancy and stability will likely improve on further iteration.

The shapes used in the test setup led ta the initial design shown in figure 52. The 3D design allows for the analyses of the rafts using different materials and sizes. On the left in figure 52 there is a solid raft from polyurethane (similar to the styrofoam used in the test setup) and on the right a hollow high density polyethylene (HDPE) raft. These materials are often used as floaters in conventional DWC baths, are light and can be shaped to fit the plant well. An added benefit is the opportunity to prototype the designed raft within the time frame of this project.

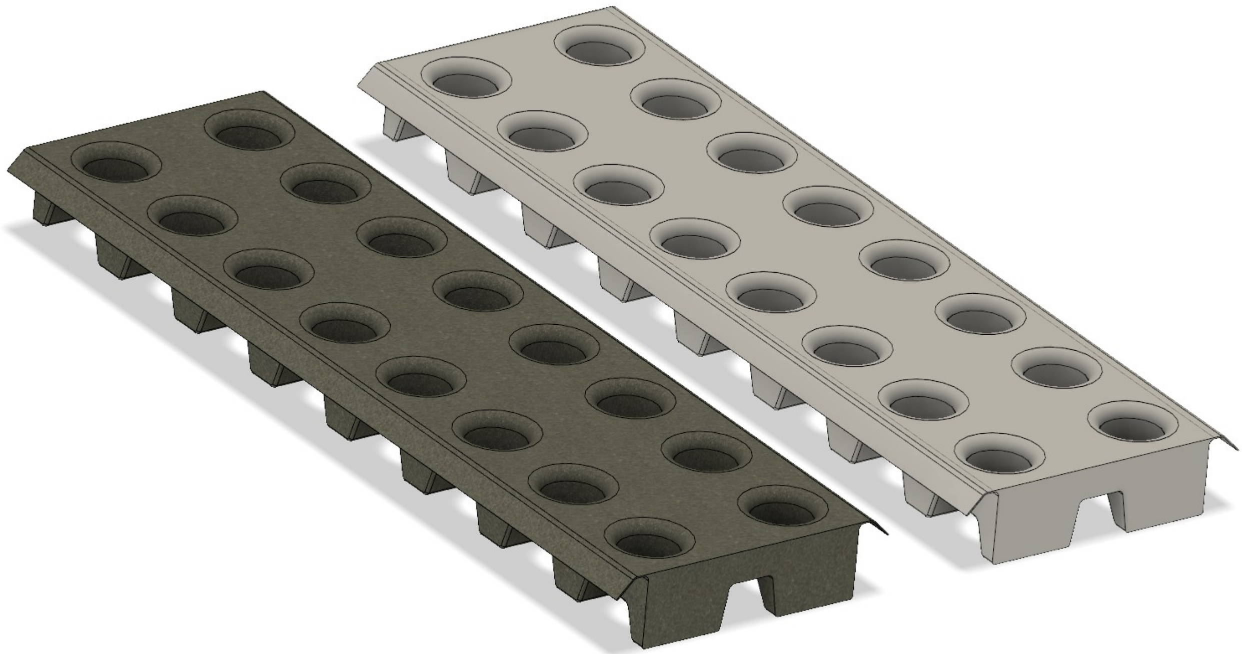

Figure 52: Different materialisations of initial design raft. Left Polyurethane and right HDPE

With respect to the material the foam raft is lighter than the HDPE raft, however the flanges are likely way to thin to hold the fruits and should be far thicker (at least as thick as in the tests). This would result in a higher and more bulky raft. The HDPE raft is heavier but is light enough to fit the weight requirement when comparing the volume of the submerged parts for buoyancy (buoyancy improves further with the appropriate number of holes for the plants per meter). Aside from this the HDPE has preferable material properties that can withstand the growing environment better. In the appendix 5.12 Details raft versions more detailed information about the different raft versions can be found, like dimensions, weight, volume and centre of mass. Note that these materials are a placeholder and a more in depth study on the specific raft material should be made by the company after this project.

This shape however is not final. Instead of using a hollow raft, material can be saved when removing the top layer. This would result in an even lighter raft since it requires less material and also means the rafts can become stackable (in an efficient way), has a lower centre of gravity and also allows for quick prototypes using vacuum forming (see Manufacturing). With these changes the raft will look like figure 53.

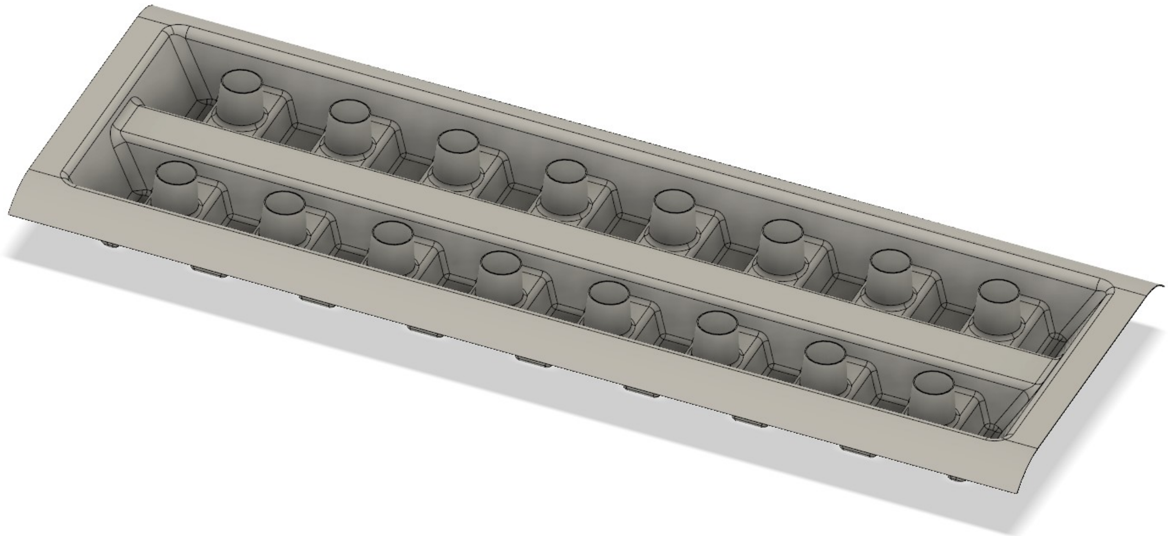

Figure 53: Vacuum form-able raft

Note that the flanges have been extended and are more rounded for a smoother positioning of the fruits and there is a slight overhang on both sides to account for the spread of the hanging fruits. The overhangs need to stand upright eventually to prevent the panels from overlapping, cutting the plant and allowing the panels to ‘push’ each other. Also, the plant spacing needs to be appropriate to the plant (for this project 8 per meter but could be different).

Final raft design

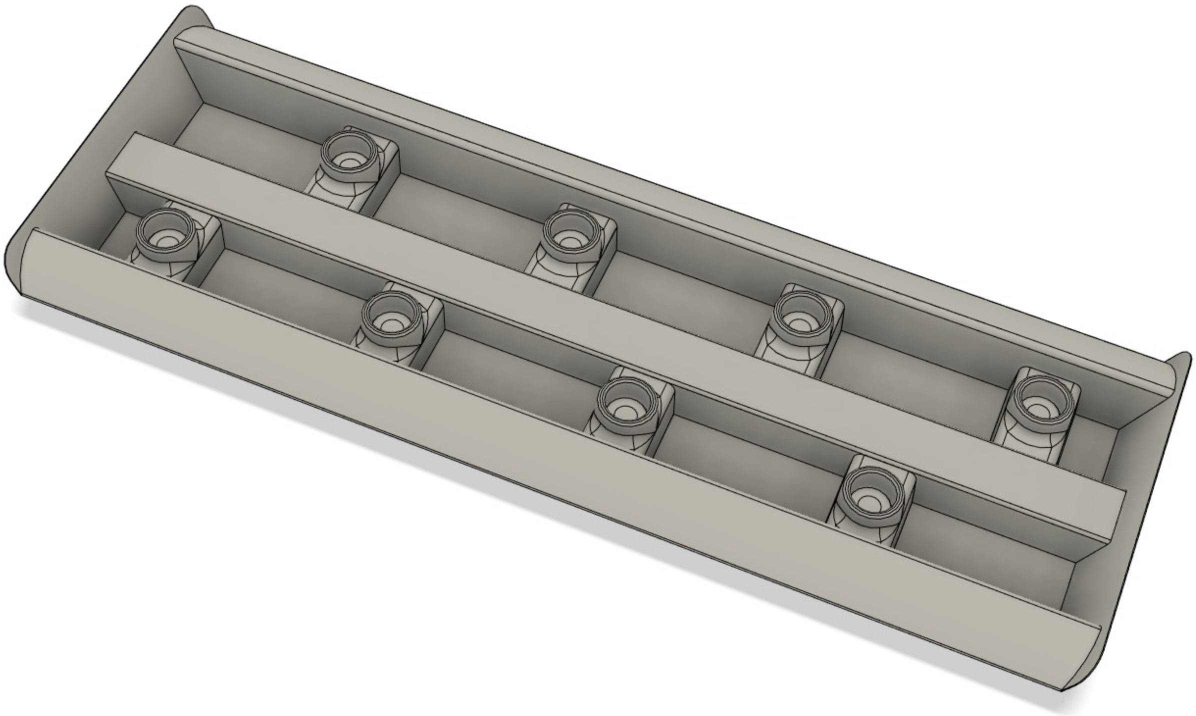

Figure 54: Final raft design

The final design of the raft (illustrated in figure 54) is created parametrically so various dimensions of the raft can be optimised like length, width, plant spacing, flange length, etc. The flanges make sure the panels can push onto each other without damaging the plants inside, these flanges can also be used to fix multiple rafts in a chain in order to be pulled from the gutter, using an elastic band for example. The complete reasoning behind this specific design can be found in the appendix Error: Reference source not found Error: Reference source not found.

Manufacturing

The manufacturing process plays a big part in the selection of the raft design. Selecting a cheap and flexible process is important since there are, depending on the size, some thousands to be made and possibly all over the world. If the tooling costs are high the preference goes out to only one manufacturer and the product might need to be shipped (and thus packed efficiently), however if tooling costs are relatively low it could be possible to manufacture the rafts on location (or nearby).

The manufacturing of durable (hard plastic) parts can happen in a variety of ways: Injection moulding, thermoforming, deep drawing, etc. The book “Manufacturing methods for design professionals” (Thompson, 2007) has served as a reference to the decision on which manufacturing process is best suitable. The initial requirements for this raft are a cheap and quick manufacture of prototypes suitable for a small cultivation cycle test run in the foreseeable future.

For the raft the manufacturing of choice is vacuum forming. With vacuum forming a sheet of plastic is preheated to make it pliable and made into the desired shape by creating a vacuum between the sheet and a mould (see figure 55). After the moulding process excess material can be trimmed off. The reason for this production process it its relatively low tooling costs and low material costs for smaller production runs. Additionally, at the faculty design engineering it is possible to use a vacuum-forming machine for sizes up to 750mm (so quick prototyping is possible). In this process only one mould needs to be machined (for small runs made from hard foam or plastic and larger volumes aluminium or steel) and thin (.5-3mm) sheets of material are used.

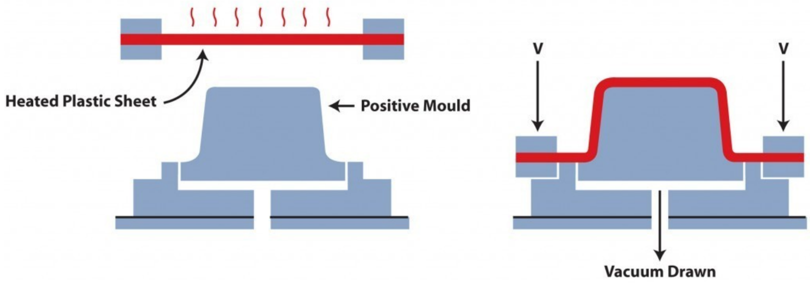

Figure 55: Vacuum forming process (Ashworth, 2016)

Some design consideration for successful production using this manufacturing method are: sloped walls for mould release, avoiding small corners to prevent sheet rupture and leaving enough space in-between the walls to also prevent material rupture. In essence the importance of this process is ensuring the available material (the plastic sheet) is able to fill all corners and holes of the mould.

The 'bottom half' of the mould is chosen instead of the 'upper half' for various reasons. It ensures there is enough material to form the plant holes, makes the plant holes sufficiently strong and it leaves a better surface finish on the top. The final design parameters (thickness, release angles, wall clearance, etc.) shall need to be discussed with a manufacturer to make sure large scale production runs go well. Some links to manufacturers websites are stated in the appendix 5.11.1 Manufacturing companies, which serves as the manufacturers list for the company.

If this product is successful and the need for large scale production would arise it could be possible that this method of manufacturing will not be sufficient. Vacuum forming requires pre made sheets that result in wasted material and post processing like cutting, trimming edges or making holes, which push the cost further from the material price. In that case the preferred production method would be injection-moulding, since it can produce far more parts at an increased speed, with less wasted material, no post-processing and more design flexibility that could improve stiffness, weight, etc. The added design flexibility also allows an additional notch/string that allows the rafts to be connected to each other. However, since mass production is not expected to happen within 1 year, eventual reconsideration on the manufacturing process and design is postponed to beyond this graduation project.

Prototype

Creating a physical prototype allows for a better understanding of the shape and size than a 3D model could, which is preferable for communication to the company. Therefore, as a proof of concept, a sample of the vacuum formed raft is made (figure 56). For the prototype a sheet thickness of 1mm is used to keep the weight to a minimum and this was the thinnest size available. First a small part was tested to find any unforeseen complications after which the entire raft was produced. Additionally this sample is used to check whether the design of the mould is suitable and the raft works according to the 3D model.

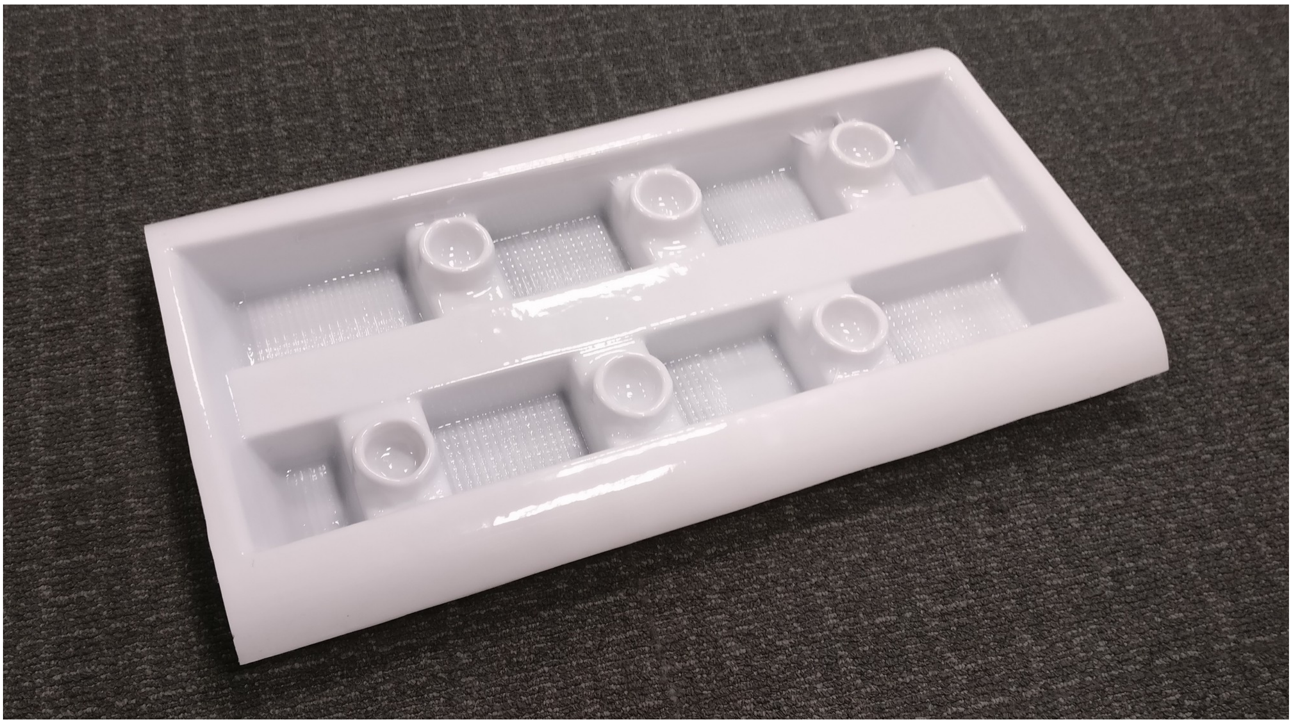

Figure 56: Vacuum formed prototype

During production of the prototype some material bridges were formed due to the walls being too close to each other (this was resolved using a plunger). Also the material became fairly thin at the bottom of the raft, which is not necessarily a problem for the prototype (since it did what is had to do). However this is a weak point in the design and would likely decrease the life expectancy and should be avoided in larger volumes (make use of a plunger or pre-stretch the material).

The prototype was tested to float on water with the added weight of 6 plants (which corresponds to the plant weight at that size). With this load it floated at a water height of 40mm, which is in line with the expectations of the 3D model aside from minor deviation in expected floating height (see appendix 5.10.7 part Buoyancy). Deviations with the model were likely due to the deformations that occurred during the manufacture and the weight of the raft material. In comparison to the model, where wall thickness is equal, the prototype walls are not of equal thickness and thus the weight and dimensions are slightly off.

Note that not all intended features have been incorporated, like upward flanges, since these were added later on in the design. Also the size of the model was limited to the machine available. Other prototyped parts can be found in the appendix 5.11 Prototyping .

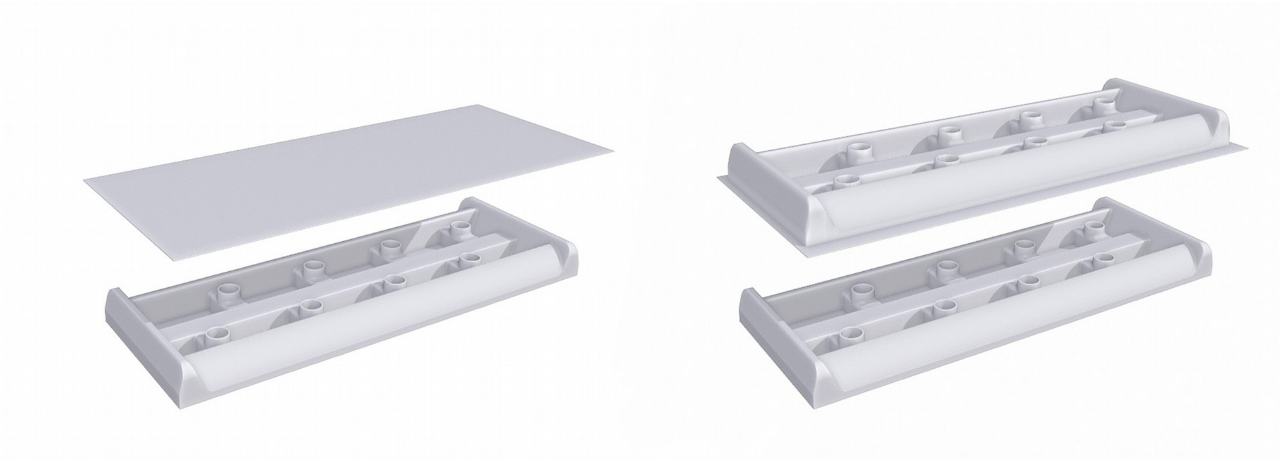

Figure 57: Final mould and vacuum forming process. The left shows the mould and sheet before vacuum forming and the right shows the resulting form.

Figure 57 shows the final mould required for the manufacturing of the raft. Further evaluation of the concept shall been done by the company, by means of a strawberry production cycle using the new rafts and gutter system.

Any future improvements on the raft regard a definite size for the plant substrate holder (depends on propagation and cultivar), a definite height for the plant substrate (depends on root development), integrated raft chain attachment point and a final length of the panel (transport logistics and weight to size ratio depended) and the exploration of an origami like form where the plants can have an increasing amount of space while growing (no separate propagation and production rooms, but prone to failure).

3.4.3 LED

LED Heat conduction

The heat conduction from the lamp through the gutter to the water needs to be measured in order to see how much of the LED heat is transferred to the water. Once this is known the required water flow can be set using the other water flow results (floating volume and nutrient volume). Cooling the LED with nutrient water is not considered viable if the heat transfer is not higher than 50% or the required water flow is higher than 1m/s. In that case the LED should be cooled separately and/or have more distance from the plant canopy.

The amount of LED heat that is transferred to the gutter is measured using a LED strip attached to a horticultural gutter with a certain amount of water in it. The heat transferred can then be calculated, since the heat capacity of water and the power consumption of the LED is known. By using the formula below an estimation can be made on what percentage of heat generated by the LED is transferred to the water.

$$Q = mc\,\Delta T$$

Figure 58: Heat absorption formula

Where Q is the heat going into the system (known), m the mass of the heated object (known), c the specific heat capacity of the object (known) and ΔT the temperature difference (to be measured).

Figure 59: LED to gutter heat transfer measurement setup. Left shows the gutter with an LED strip attached to the bottom (emitting the pink light). The two right images show the temperature measurements sensors used.

ΔT was measured using the test setup shown in figure 59 (see appendix 5.10.8 LED Calculations). The results showed that around 50% of the heat generated by the LED gets transferred to the water, so 25% of its power (given that around 50% of the consumed power is heat). This amount of heat transfer is considered to be significant so the nutrient water can also serve as LED cooling. An even higher heat transfer efficiency is expected when the LED is completely encapsulated by the gutter (the two sides also). However, the tolerances of the gutter will influence the contact area and this therefore needs to be investigated further.

3.4.4 Nutrient flow Capacity

By rearranging the formula of figure 58, the required water volume per second can be calculated from just the LED power installed.

$$m_{Water} = \frac{Q_{LED\ power * efficiency}}{c_{water} * \Delta T}$$

Figure 60: Water volume required per second to cool LED light

For example, if the water should remain within a 2 degrees temperature difference (ΔT) and there is a 175W LED light attached to the gutter ($Q_{LED\ power\ *\ efficiency}$), the amount of water that needs to flow over the LED to keep the water within the required temperature difference is 0.005 L/s. This value linearly increases with an increase of the LED power and circulation length, e.g. if an LED that is twice as powerful is used, the water flow should increase two fold as well. Similarly if the water needs to cool 2 meters of gutter with LEDs the water should, again, flow twice as fast.

Since there is a water in and outlet every other 5 meters (homogenous nutrient supply) the flow should be sufficient to stay within the required temperatures along a total of 10 meters of LEDs before being recirculated and cooled. Therefore the capacity per gutter should always be 10 times higher than what is calculated from figure 60.

As a size comparison, a steel pipe with a diameter of 5cm has a maximum flow of around 2.8 L/s (Engineering ToolBox, 2004). Meaning with a 175W LED per meter a 5 cm pipe could provide sufficient water flow for cooling 560 meters or 56 gutters of 10 meters. More on how this irrigation is distributed within the cultivation area of the final concept is described in 3.5.3 Parts.

LED Gutter connection

Given that it is possible to use the nutrient water to cool the LED, an actual method of fixing the light semi-permanently should be determined since it should be fixated for several years and replaced at the end of life. The LED should be attached to the underside of the gutter and has to have a sufficient contact area for heat transfer to the gutter and water, preferably more than one side to improve heat transfer. Figure 61 shows the different suspension mechanisms which could be used to do so. Without this short exploration the installation of the LED might become more complicated than it currently is, especially due to the high density needed for indoor farming. The criteria for selecting a suitable method are ease of installation, surface area and mechanism simplicity. A universal mounting mechanism is also preferred, that is not limited to the lighting options, since the LED will likely differ for each cultivation project.

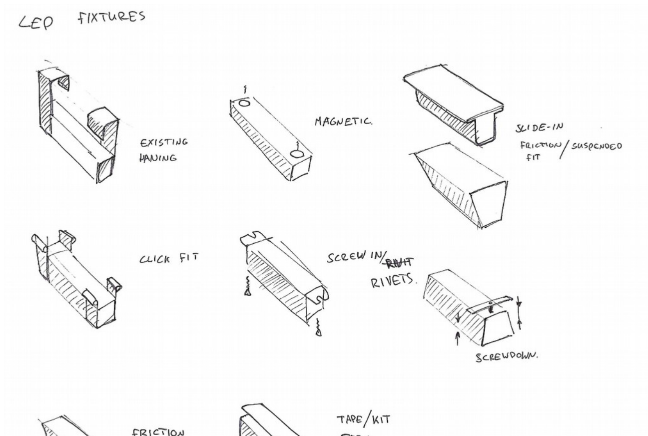

Figure 61: LED fixture variations

Screwing into the gutter is not an option since this is prone to leakage and requires the making of additional holes which have to be correctly spaced for each specific lamp. A click fit mechanism has to be well thought through to prevent failure and requires a gutter that is suitable for the click fit mechanism. Similarly, making the lamps friction fit could fail due to deflections in the gutter when suspended over long distances.

The use of magnets for fixating the LEDs is considered to be a quick and durable manner of fixing the light to the gutter. No special gutter design is required needed with click or friction fit, neither are holes which have to be screwed into the gutter and magnetic holding force is easily changed with bigger magnets. Also, most horticultural LED lights have a hole or slot to suspend them from and can be used to fix the magnets to (see figure 62). There is also flexibility in LED spacing and it can be mounted on virtually any gutter since the magnets are attracted to the steel core.

A problem that can arise is its ease of installation and replacement while having enough holding force. The lamp should not fall off even if magnets lose neglect-ably little holding force overtime and should not fall due to vibrations or collisions which might possible occur at some point. However the magnets should not be so strong that human removal becomes virtually impossible.

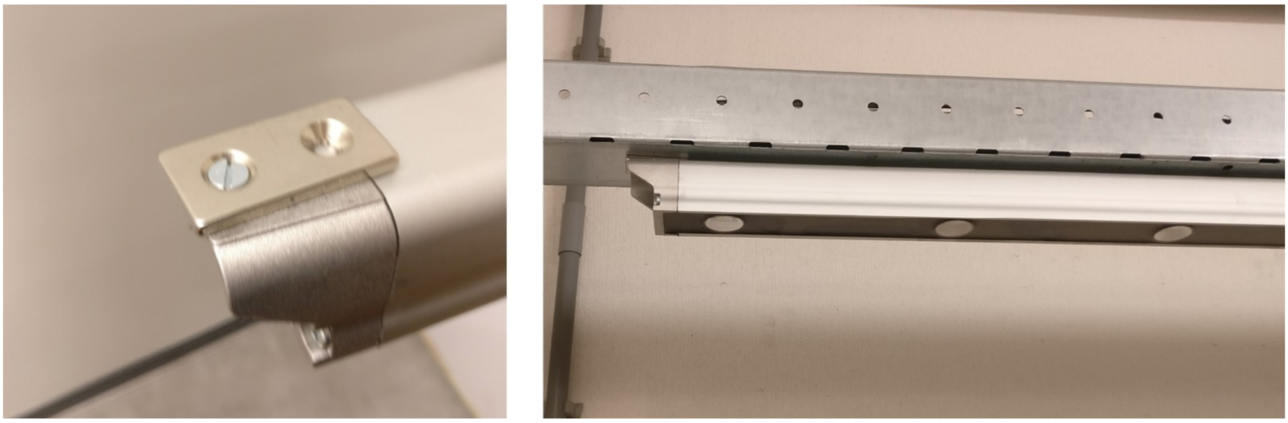

Figure 62: LED magnetic fixture connection.

A small test was conducted to check the holding force of an LED lamp with two 12kg holding force magnets (see figure 62). This size magnet proved to have an abundance of holding force while not being too strong to (re)move it from its fixture point. The fixture used in the test does influence the heat transfer negatively, so a custom mount might be required. However, when the gutter makes sufficient contact with the sides of the LED, a small gap from the top to bottom might not be an issue (this would need to be addressed in the future).

Air duct integration

The integration of the air duct into the gutter comes purely down to costs. Comparing the costs of the conventional system and the proposed version gives an answer to whether it is an idea to pursue. The cost comparison (shown in Appendix Calculations) indicate that a gutter air duct would be around 4-5 times more expensive than a normal plastic air duct. This means the gutter will not have the additional functionality as air duct.

However, since the air needs to circulate between the crops and there is already little space available it might be interesting to see if it is possible to ventilate from top to bottom as illustrated in figure 63.

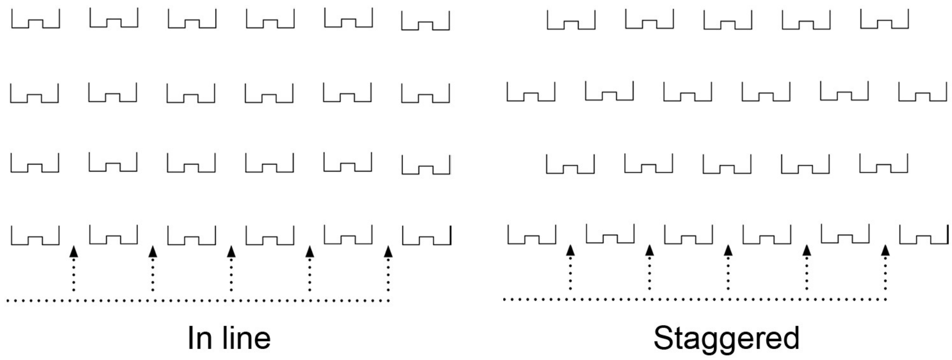

Figure 63: Air flow through gutter stacking without air ducts

Conventional greenhouses uses air ducts stretched over hundreds of meters and take up a significant amount of space. When growing vertically it might make more sense to ventilate vertically. A floor and ceiling mounted air diffuser could be a solution for homogeneous airflow while keeping costs to a minimum. Additionally the spacing of the gutter could influence the way the air flows around the plants, so there will be a difference in placing the gutters in ling or staggered (figure 63). The flow around the gutter will likely be more turbulent in the staggered orientation, however which method is more beneficial should be determined.

3.4.5 Transport

With the transport of the high density area defined only a part of the problem is resolved. The remaining step is moving these plants from the high density area to a low density one, where labourers (or robots) can easily access the plants for planting picking and removing . Initially this step was considered to be outside of the scope of this project and would be likely be a concern of external parties later on, probably using some sort of conveyor system. However, the costs of transport using conveyor belts can become quite expensive should the raft to go all around the structure to complete one picking cycle. Especially when doing so on multiple layers. Thus, a short exploration on the raft transport path is presented which resulted in a transportation method far more cost and space efficient than a traditional conveyor system, like those used in lettuce transport.

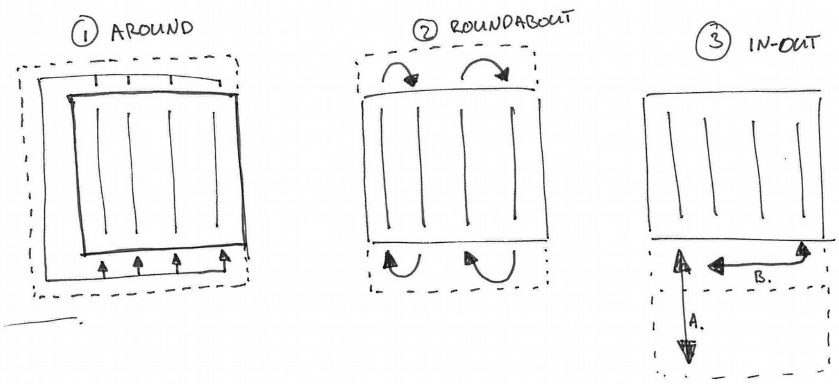

Figure 64: General transport directions methods

Figure 64 shows 3 general ways of removing a chain of rafts from the high density growing area to a central picking location. The lines inside the square box represent the gutters the box itself the growing area, the dotted line show the additional room required for transport and the arrows indicate the transport path.

Method 1

The first method '1 around' is to take it out on one side, move it around the structure and put it back in. The problem here is that it requires a method of picking and placing the raft in and out of the gutter while ensuring a continuous loop for picking continuity. Also, as said before, conveyors are expensive and take up a significant amount of space (here it goes around three sides of the growing area) and are thus not suitable.

Method 2

The second option '2 roundabout' is similar to the method used in the initial concept and is creating small cycles where the ends of the chains are made into a loop. Unlike the first there are only two sides where some sort of mechanical transfer need to happen. It is also possible to do this transfer via the water but this could give rise to complications regarding its movement, open water and clearance for rotating a raft around a corner. Any other mechanical movement however could become expensive due to the many short cycles and the movement having to be in-sync with the other side (which is prone to failure). There is also no obvious way of clearing out the entire loop at the end of the growing cycle. Also the use of this rotation reduces the accessibility of the plant on the inside of the loop.

Method 3

The third movement '3 in-out' would comprise of a system in which the row of plants is completely removed from the gutter and pushed back in after harvest, like a drawer. In this way both sides can be harvested at the same time during retraction. Once a row it cleared the pickers move to a different gutter and harvest the fruits there while the previous gutter goes back. This mechanism only requires one side for harvest, but takes up quite a lot of room and labourers need to wait for the entire chain to retract before going to the next (or need to move up one layer).

Final transport method

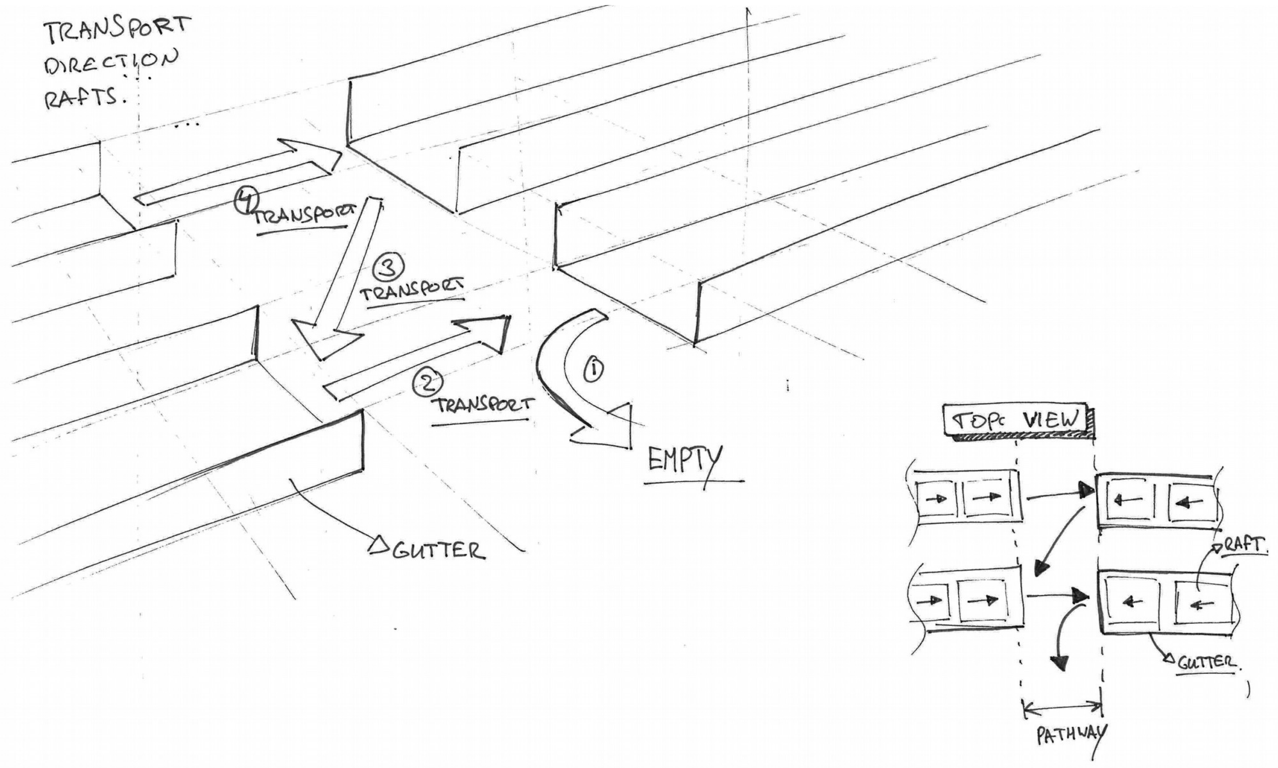

Figure 65: Transport of rafts from gutter

A more space and transport efficient manner of movement has been thought of combining the methods of figure 64 into a back and forth steam, eliminating the use of long transport lines around the system and the need for a lot of empty space. The proposed method becomes a way in which a continuous supply of fruit can be achieved by replacing the plants of each gutter with the next (see figure 65). By removing the plants from the first gutter (plants that have gone through the entire growth cycle) an entire gutter becomes available to place the next row of plants into. Since the plants need to be moved during harvesting they can slide into the just emptied one. A row of plants should zigzag through the growing stages, advancing one gutter with each harvest. Once all plants have been relocated into the adjacent one there remains one gutter empty. This last gutter is then filled with new seedlings. Figure 66 shows the movement for this process in different steps.

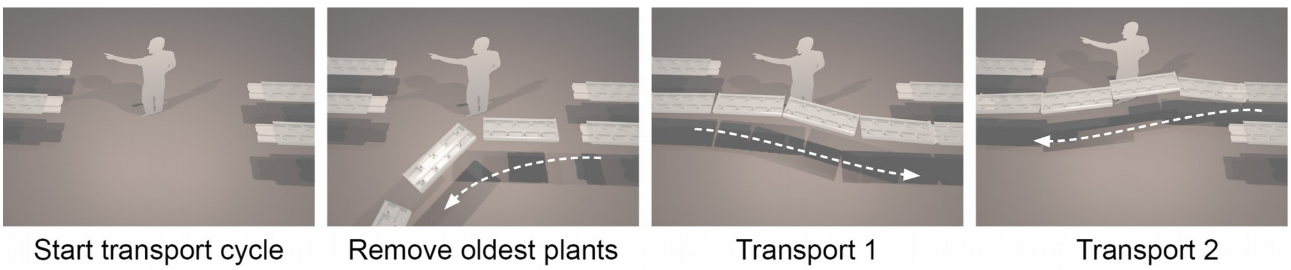

Figure 66: Transport cycle steps

Addition space can be saved if the gutters are spaced to suit the specific plant stage. When the plant is not yet bearing fruits the gutters can be closer together and as the plant grows and moves through the facility the gutter spacing increases as well. However, this does require very precise knowledge and control regarding the plant growth and thus limits flexibility.

The only thing left is the design of a mechanism which can take out the row of rafts from one gutter, position it so workers can easily pick the fruits and then place it in the next gutter. This could happen using a short and flexible conveyor system which can be moved through the pathway to reach each gutter. This conveyor cart should also be able to move up and down to harvest the other layers. Such a cart is more advanced than current picking carts and will thus be more expensive, however these costs are not expected to be higher than other transport methods, especially those which go all around the growing chamber on all the layers.

3.5 Final concept

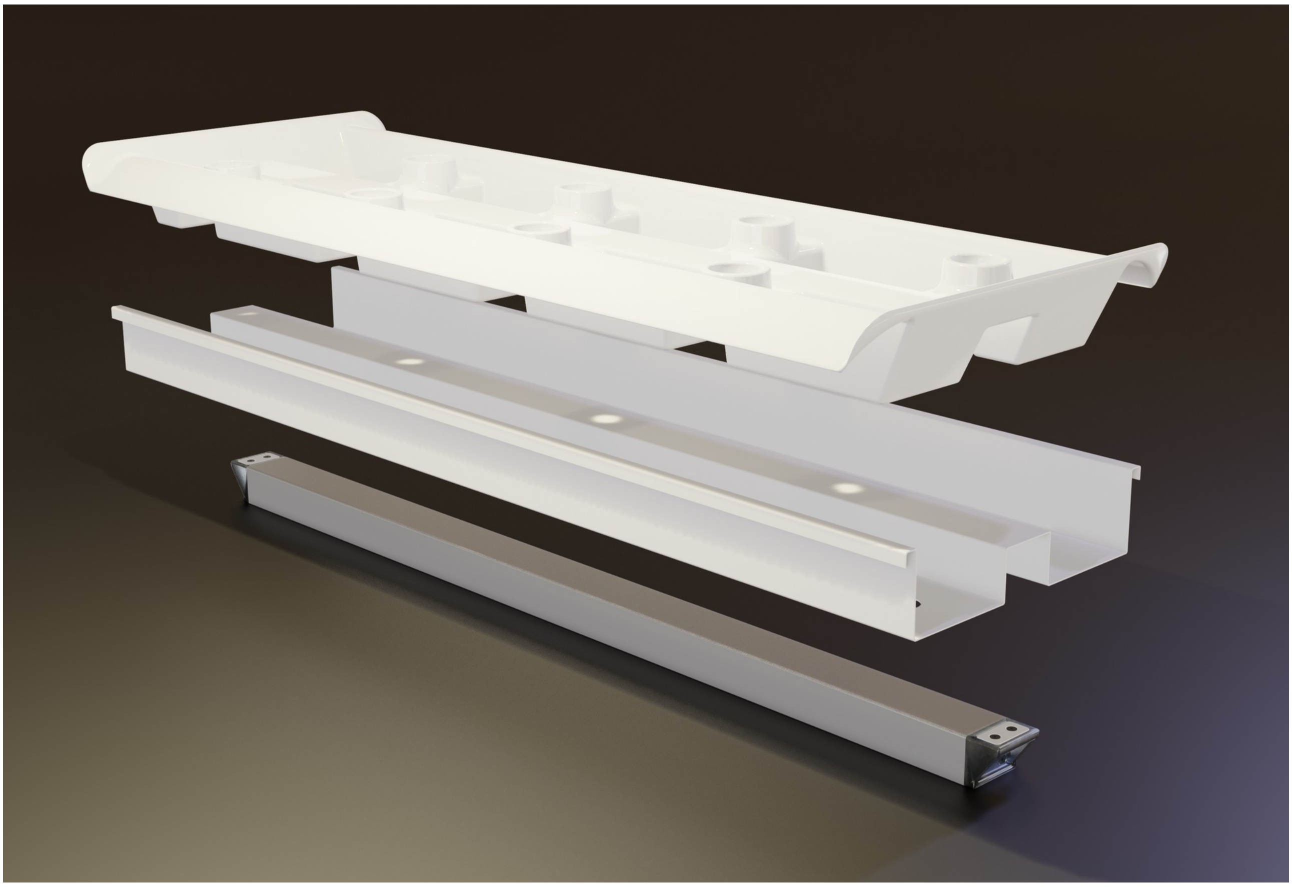

Figure 67: Final concept exploded view of main components

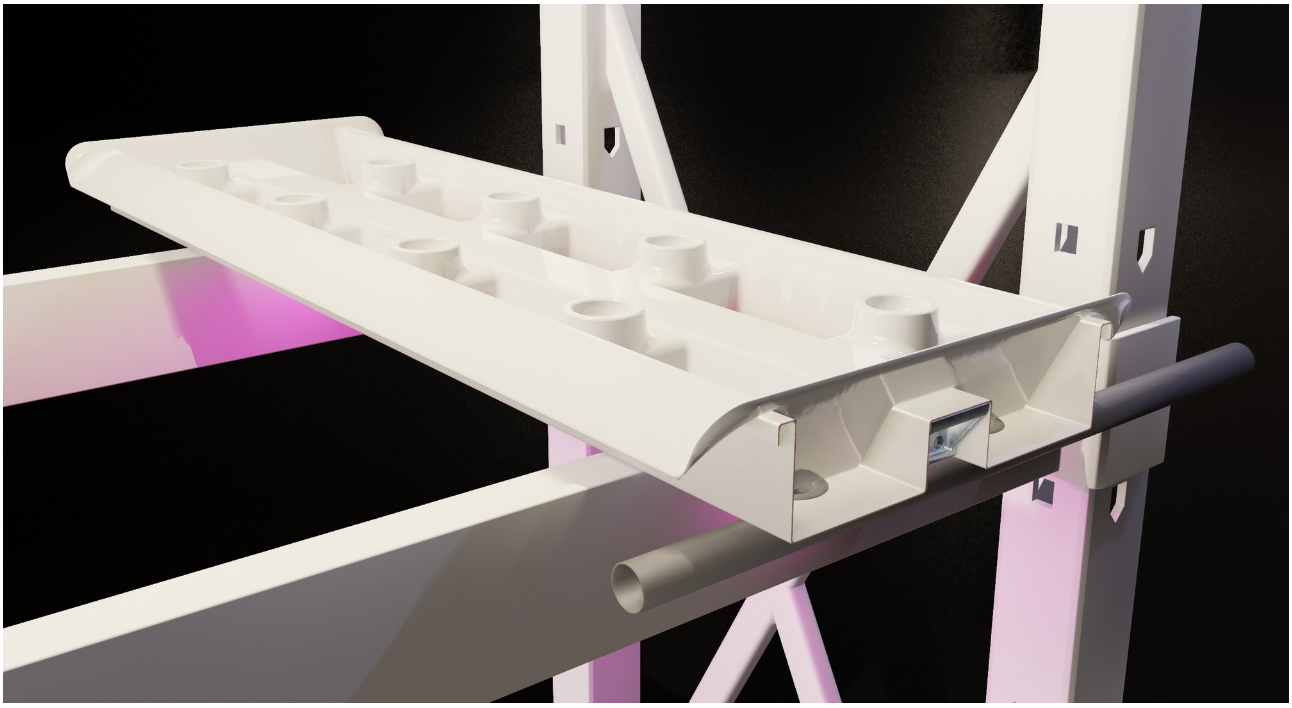

Figure 68: Final concept on pallet rack structure with gutter and irrigation segments

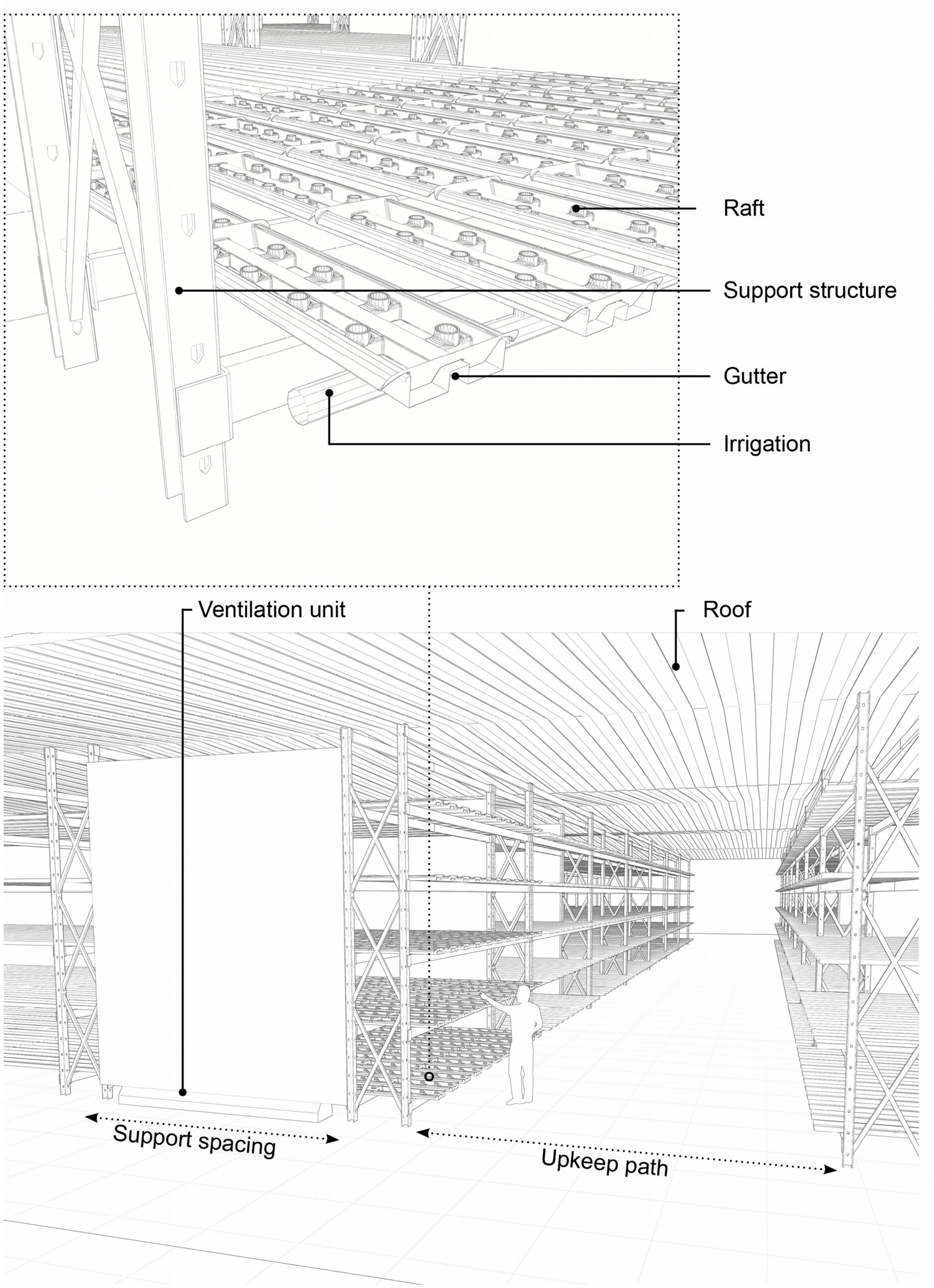

Figure 69: Final concept example system

3.5.1 Concept description

The concept (see figure 67 and 68) provides a novel way of growing crops at a high density indoors. It integrates several features that make it more cost effective to grow food vertically in comparison to other indoor systems. The main benefit is its capacity to not sacrifice space efficiency for accessibility while doing so in a cost efficient manner (see chapter 3.5.4 Estimated cost changes). This is partially achieved by, higher plant density, increased LED life and cost effective structure and less moving parts. The main components are the raft, gutter and LED light.

The concept makes use of conventional cultivation gutters which are placed on pallet racking structures spaced 4-5 meters apart (see the support spacing in figure 69). Unlike the conventional usage of gutters where plants remain stationary, here plants are placed in rafts and can be transported on the gutter using the very little amount of water that flows inside. This nutrient water continuously flows through the gutter to provide nutrients for the plants and cool the LED lights. The notch in the gutter surrounds the led on 3 sides for optimal heat transfer to the water. By increasing the water level in the gutters the raft will float and thus the plants are transported.

Over 90% space efficiency can be reached since plants are cultivated at a high density in a growing area and transported for harvest to a central picking location. This method of transport is inexpensive, since there is little to no mechanical movement needed and the transport distance is minimal. A simple push or pull at one side is enough to drag an entire chain of rafts 50m long and only needs to move across the upkeep path as described in 3.4.5 Transport. In the appendix a complete list of the benefits of this system are stated (see appendix 5.13 Final concept benefits).

3.5.2 Usage

This system is intended for large scale commercial production of fruits and vegetables. Its primary use case is the cultivation of strawberries. However, as long as the plants size and weight can be supported by the raft, it is also possible to grow other crops like basil, lettuce or other relatively small crops.

Primary usage is intended for crops where multiple separate harvests are required like for strawberries. In this case the plants need to be accessed every so often. At first, plants are propagated from the seeds in small substrate plugs. Once they are big enough these small plants are placed with plug in the holes in the raft. The raft placed on a gutter and moves from one gutter to another on the opposite side. Every time a rafts crosses the upkeep path there is a possibility to harvest the fruits and rearrange the leafs and fruits. Since plants are located on both sides of the raft there should be two labourers on each side. Depending on the width of the upkeep path more labourers can be working on the same side.

Exact transport and cultivation management of the crops can differ depending on the needs and wishes of the cultivator. It is, for example, also possible to grow the plants in several batches instead of continuously by keeping one gutter empty and having the rafts go back and forth between two gutters. Or, when there is no need for multiple harvest, there can be an in and output side for each gutter. This system can also be used for non vertical indoor systems or greenhouses.

3.5.3 Parts

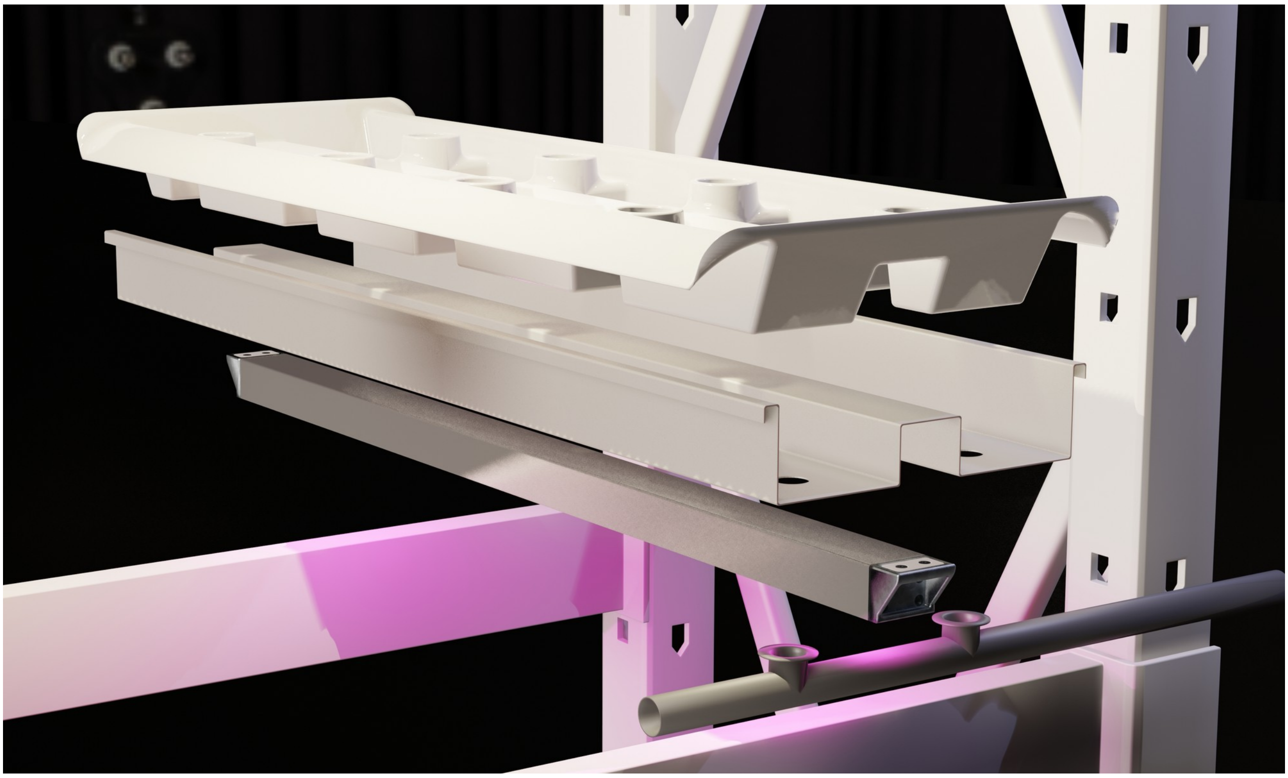

Figure 70: Final concept exploded view

The purpose of this part list is to show all components which influence the design together with their purpose. Note that it is not a complete list for building the entire climate-cell production facility with rooms for offices, external transport, etc., since this is unnecessary and too general information for both the company and this report. This list should be used by the company to 'connect' the remaining climate-cell parts to. Figure 70 shows the locations of the different parts. The purpose of each component shown is described below.

Raft

The raft holds the plant and serves as a floating transportation method (see figure 71). Young plants are positioned in the different holes which allows them to develop their roots into the water below. The fruits that develop should be organised in such a manner that the fruits lie on the side flanges and hang to the sides of the gutter.

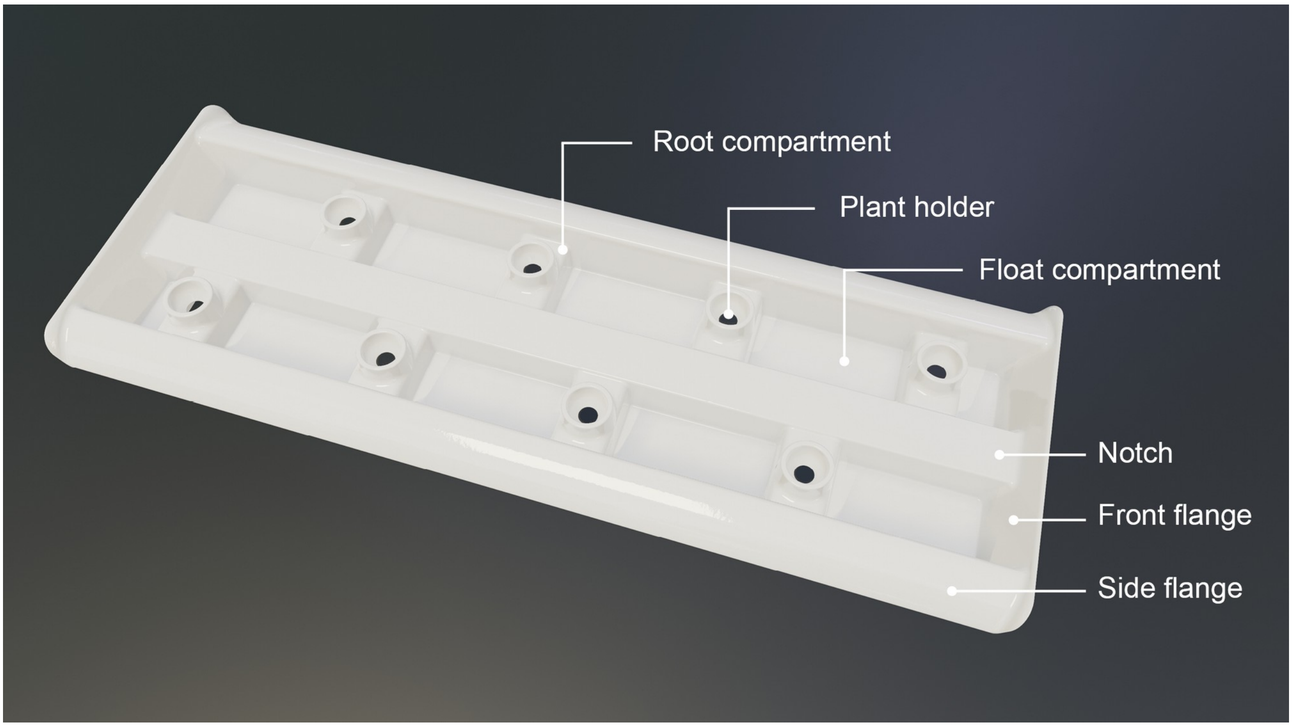

Figure 71: Raft part features

The raft in figure 71 has room for 8 plants and is roughly 1 meter long, 30cm wide and 8cm high. Depending on what is cultivated using the rafts the size and plant density can differ.

Gutter

The gutter contains a notch that holds the LED, has two compartments where water flows through and attachments for the irrigation in and outlets (see figure 72). It will fill with water at a varying height and flow-rate which provides nutrients to the water, cools the LED and allows the raft to be transported along the entire gutter.

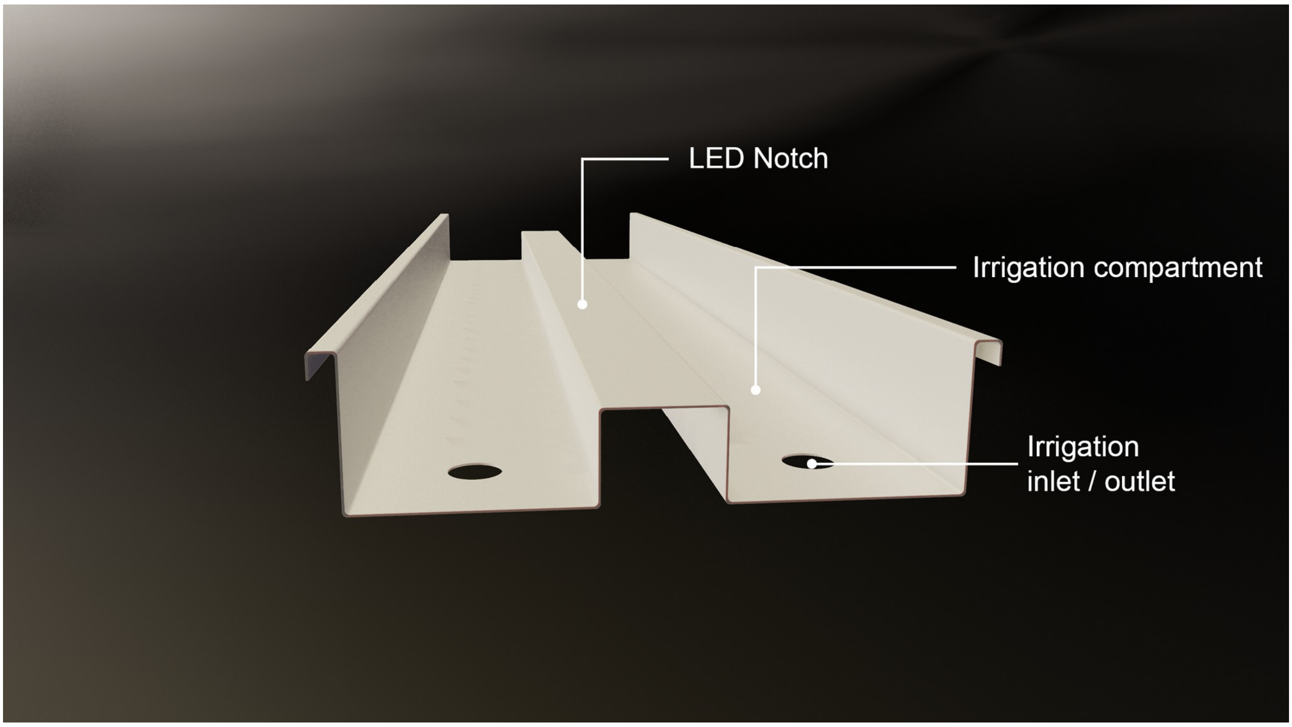

Figure 72: Gutter part features

The shape of the gutter is derived from already existing gutters and can therefore be manufactured without further development. The only requirement is that the LED light will fit inside the notch of the gutter and should thus be dimensioned accordingly. The gutter shown in these part renders are only a small section, in reality these gutters can stretch 50 meters or longer.

Both sides of the gutter will require a cap that prevents the water from spilling out of the gutter on either side. The cap that faces the upkeep path should be made in a way which allows a transport machine to take the rafts out of the gutter to be harvested after which it places it in another gutter (explained in 3.4.5 Transport).

LED lighting

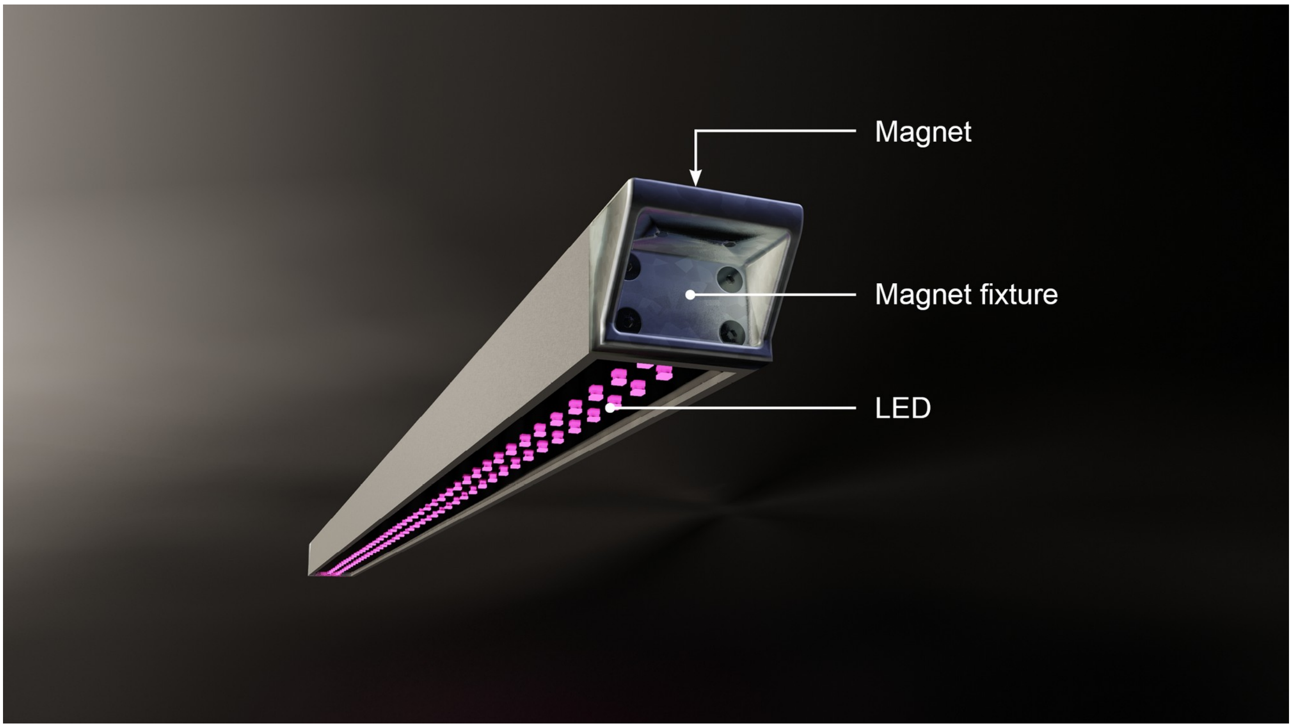

Figure 73: LED part features

The LED provides lighting for the plants and can be fitted into all gutters from layers 2 and above with magnets. The first gutter does not have any plants underneath so no lighting is needed there. The top most layer of LEDs cannot be placed in a gutter and has to be suspended in a more traditional way or could be magnetically fixed to the roof if possible. These uppermost LEDs are likely not water cooled and may last less long compared to those that are.

The precise specifications and dimensions of the LEDs cannot be defined since this is highly dependent on the crops and distance. However, most lights are around 5 cm in height and width and are between 80cm and 120 cm long.

Irrigation

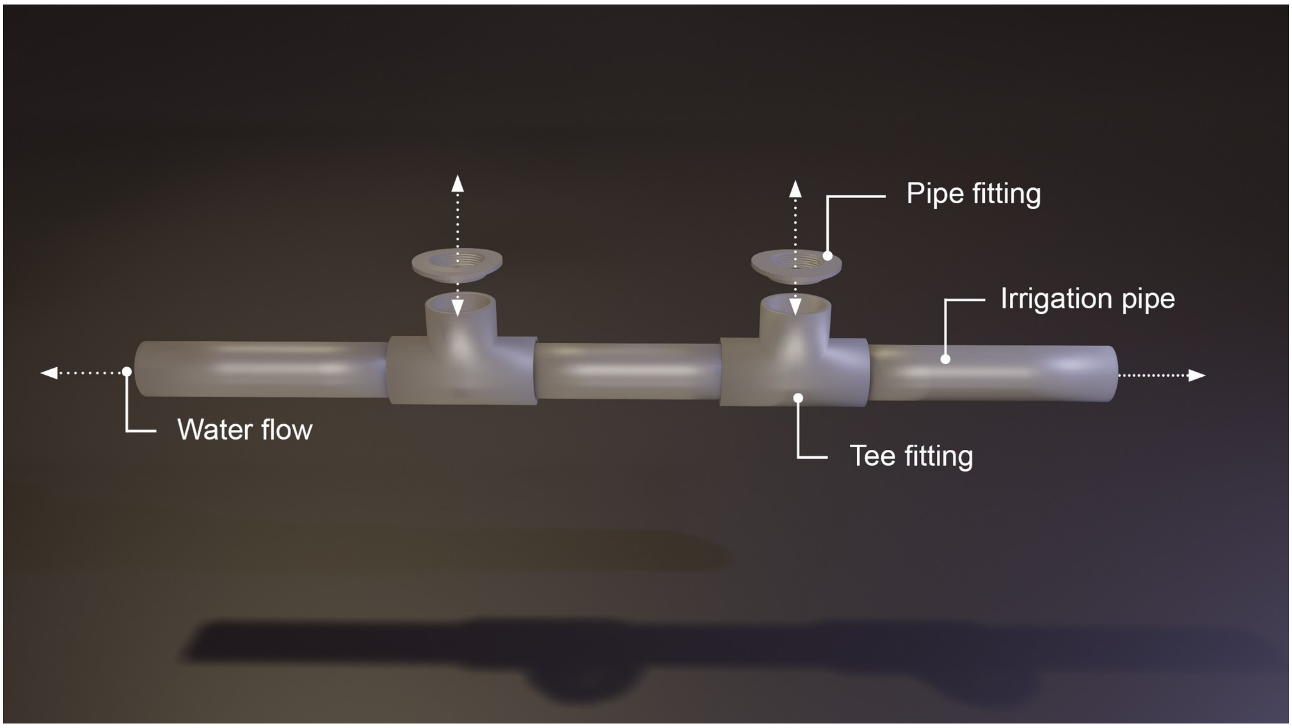

Figure 74: Irrigation part features

Irrigation is fixed directly underneath the gutter and allows in and outflow of the nutrient water. Water can flow can occur in both directions depending on the location, as indicated by the arrows. One irrigation pipe connects to several adjacent gutters. The irrigation connects to each gutter at a certain interval and provides a water in or outlet. Irrigation is fixed directly to the support structure at the same interval with an in or outlet every 4-5m. This interval ensures both a homogeneous nutrient supply and temperature distribution while keeping the flow to a minimum. The irrigation pipes can be fixed onto the beams of the support structure using a U-bolt or other fixture. Specific dimensioning of the pipes should be individually calculated per case and is highly depended on the amount of gutters it supplies to and the lights installed.

Structure

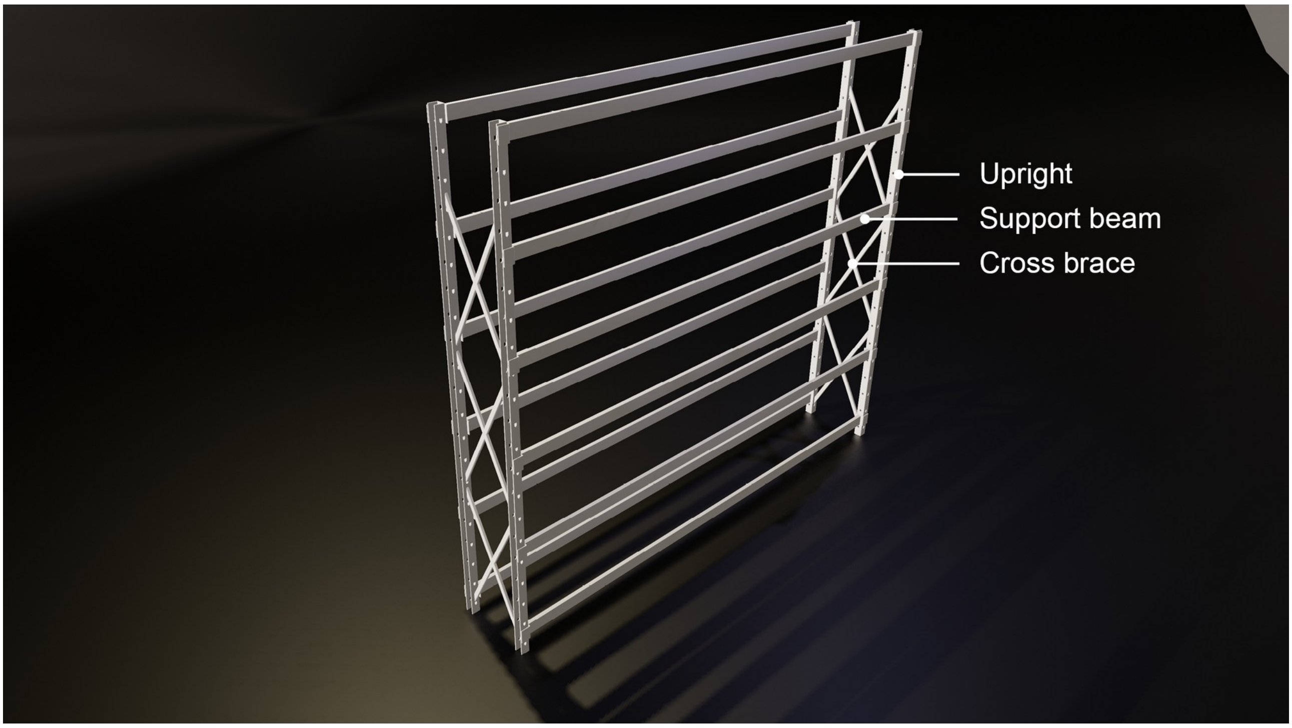

Figure 75: Structure parts

In the final concept pallet racks are used to support the gutters and make sure they can be positioned above each other at a low costs. The distance of the different layers can be changed incrementally according to holes present in standard pallet racks.

Additional height spacers may be needed to prevent the strawberries from hitting against the beams that support the gutters. This spacer creates additional space between the gutter and beam. Note that if the cultivation cycle mentioned in chapter 3.4.5 Transport is used, this spacer only needs to be used on gutters that hold plants that are bearing fruits and not on the gutters were the plants are merely in the vegetative state.

3.5.4 Estimated cost changes

At the beginning of the report the costs of a climate-cell was explained. This analysis indicated the parts that made indoor farming so expensive. The whole point of the report is to make indoor cultivation more economically viable for large scale commercial production. So the question becomes "Is this new method of cultivation cheaper than its predecessors?". This method of cultivation uses the climate-cell significantly more efficiently and saves costs due to the various reasons explained below.

1. Fewer sandwich panels needed

   Plant density in comparison to greenhouses and climate-cells are greatly improved. Without the need for pathways between the crops plants spacing can be twice as low. While the compacting and integration of the components saves significant space as well. Depending on which systems are compared a 2-10 higher plant density can be achieved within the same space. For example, the Certhon facility has a gutter spacing of 1.6m with 3 layers. The concept can with a similar layer spacing and no need for paths achieve 6 layers and a gutter spacing of 0.5 meter. Thereby producing around 6 times more in the same space reducing the cost of sandwich panels per kilogram of produce by 83%.

2. Higher LED lighting efficiency and longevity

   According to the data sheet provided by Certhon the light efficiency of a hoist gutter system spaced 0.6m apart is estimated at 85%. With the same gutter spacing the concept lighting efficiency would be equal or higher because the light that would have hit the floor in the original case has a chance of hitting the crops located on a lower level. Only the light of the lowest level cannot be more efficiently used, but for a system of 5 layers high this is only 1/5 of the lights that are in use. With a conventional gutter spacing of around 1 meter the lighting efficiency lies around 70%. This means at least a 15% increase of efficiency is achieved.

   15% better light efficiency has both an influence on the investment and running costs since both less lights need to be installed and less power is consumed.

   The LED light is also expected to last up to 40% longer besides the improved lighting efficiency through the compact design. Keeping the LED far more efficiently cooled using the nutrient water will increase the products lifespan and thus lower the investment cost due to the lower depreciation.

   Note that a lot of factors can influence the actual lighting efficiency and increased life expectancy and thus conciser this a rough and general estimate. The precise cost change depends on what light is used and is not provided.

3. Potential Labour reduction

   The system makes use of automated transport where the labourer would not have to move. As described in the chapter 2.5 Automation and vertical systems there is a possibility to increase labour by more than 25% and save up to €30,00- per hectare when making use of the right transport systems. Although the system should be able to transport a chain of consecutive rafts and possibly optimize picking speed, cost reduction by labour reduction is not yet considered without the further development of the device which enables the transport. However, this will likely have a positive influence.

4. Less complex Transport

   Not only does the improved plant density low cost by more optimally using the climate-cell, but also the lack of complex transport systems that require space. As explained in chapter 3.4.5 Transport there is wasted space when transporting the plants around the system. The transport of this concept is far more compact since the rafts are transported to and from opposing gutters. Therefore no input and output line has to be constructed and no expensive transport connections via belts have to be used.

   Though the transport mechanism should still be developed by Certhon, the movement of the raft is simple and the object of transport a fixed shape. The raft only crosses the upkeep path and one transport device transports the rafts in all different gutters. Therefore, this device should not be more expensive that any conventional roller transport system which cost between €155-€195 per meter (Raaphorst & Benninga, 2019) and is needed on all layers. Cost will likely be comparable to a scissor lift or forklift which are €14.000-€45.000 (Raaphorst & Benninga, 2019).

5. Structure

   Instead of being carried by wires like conventional greenhouse cultivation, the gutter are placed directly on pallet racking structure. Cost for the gutter suspension systems cost roughly €1,- per meter gutter while systems which allow gutters to be moved up and down are around €6,- per square meter (Raaphorst & Benninga, 2019). In comparison to the cost per meter with the use of the pallet racks mentioned in chapter 2.5.2 Vertical farms the costs of this concept is no more expensive than conventional systems at a price of €2-€7 depending on how well the capacity of the structure is used.

6. Rafts with NFT

   Substrate holders, irrigation supply and other cultivation necessities are always required, therefore these parts including the rafts are not considered to be any different to conventional systems. However, the floating rafts are similar in function and as conventional polypropylene substrate holder bins of 133cm by 20cm and should thus be similar in price of €3.35-€3.95 per piece (Raaphorst & Benninga, 2019).

3.5.5 Installation steps

The order in which the entire structure is build is described here in rough detail and functions as an initial installation proposal. The high plant density leaves a lot less room for installation which means it should happen in a specific order. The specific order could be reconsidered (hence proposal), but the little space available has to be taken into account or it might become unnecessarily complex. The build process is similar to that of a warehouse (derived from Mecalux, 2016). Figure 76 shows the relevant steps for the installation of the concept.

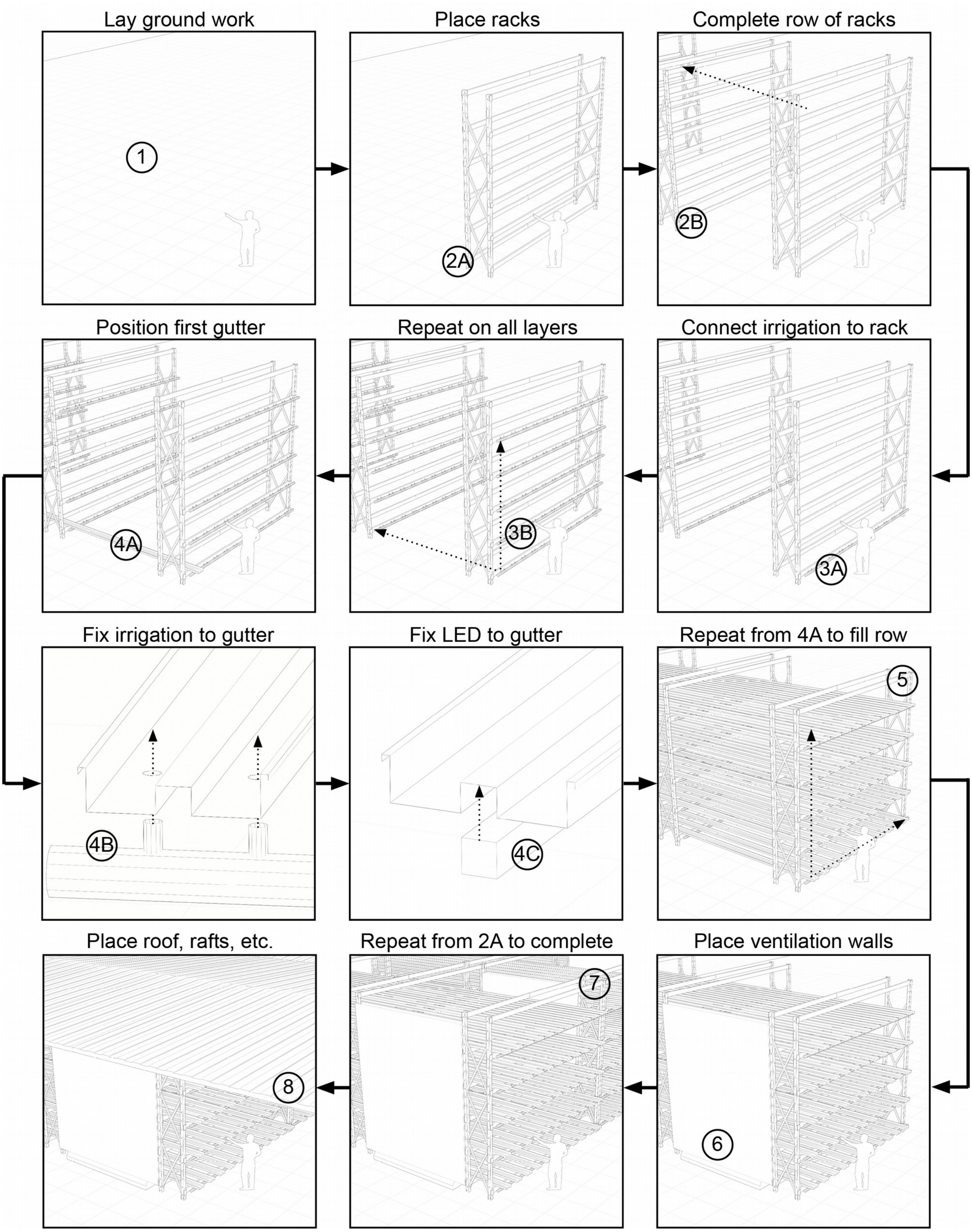

Figure 76: Installation steps

Step 1 Groundwork / Foundation
Lay the groundwork and pour (reinforced) concrete. The entire structure shall be built on this concrete flooring and requires no slope for drainage, the floor should be level.

Step 2A &B Install row of pallet rack sections
Positioning of uprights and laying the beams for one row of sections. All beams should be on the same height for each level or can be slightly lower for the drains.

Step 3A &B Fix irrigation per section
Fix irrigation and drainage pipes along the pallet rack section beams in order to later on connect the gutters to the irrigation in- and outlet.

Step 4A Place gutter
Position the gutter directly on the beams or on height spacers (should be placed beforehand on the beams). Ensure there is enough space (likely 1.5-2 gutters per meter) between each gutter to make room for hanging fruit and air ventilation.

Step 4B Connect gutters to irrigation
Attach each gutter to the irrigation inlet and drainage pipes. Drilling holes in the gutters might be required or the holes are punched into the gutter beforehand (could complicate things due to alignment).

Step 4C Place LED underneath gutter
Position the LED in the gutter slot making sure to align them in a way in which the light from the LED is not obstructed by the beams, spacers or irrigation pipes.

Step 5 repeat gutter placement to fill row
Position all other gutters in a similar matter following the steps from 4A to ensure ease of accessibility to the irrigation connection and LEDs. Not doing so does not make installation impossible but harder to do, since the available space becomes limited with the surrounding gutters installed.

Step 6 Place air ventilation walls
Any aeration systems that are positioned between the racks with gutters should be installed before installing the adjacent racks. The racks may be placed further apart to leave a small hallway for maintenance purposes.

Step 7 repeat steps to complete the facility
Repeat the steps from step 2 with the remaining rows of gutters to complete the structure. Multiple rows may be build after each other without placing the gutters (step 4) though the gutter placement should happen in a similar fashion.

Step 8 Fix roof to pallet rack section and other remaining parts
If the pallet rack is used as a structure for the roof the roof will need to be fixed to the racks. This could be done once all sections are installed, however due to the installation of the LED on the gutter it might be safer because of outside climate conditions to place the roof immediately (though the LED should be able to handle it).

End caps have to be placed on the gutters to prevent water from flowing out (not shown). This can also be done right before the gutter is manufactured on-site and after it has been cut to length. Further installation includes the remaining building facilities, rooms, etc. and other cultivation related parts like electronics, irrigation pumps, dehumidifiers, etc.

Again, this process is not yet permanently set. However the importance the two cycles illustrated in figure 76 is strongly advised due to the limited space and the lack of gutter support. If the irrigation and LED placement would happen after roll forming all the gutters, there would be very little space to do so, resulting in more labour and safety issues. Similarly, if all gutters are formed and placed beside each other instead of one per layer, it could complicate the installation process due to the accessibility.

3.5.6 Final check with requirements

Here the final concept is evaluated to the previously set up list of concept requirements. This evaluation with the requirements serves as a checklist to ensure the concept takes all core necessities into account. Also, all requirements which could not be met due to the project duration are mentioned ensuring it will be resolved at a later stage. These next steps of the project are briefly discussed in 3.5.7 Recommendations and further improvements and in more detail in the appendix 5.14 Further system improvements developments.

1. Suitable for strawberry production indoors

   The final concept is suitable for strawberry production and allows for its proper cultivation.

   The raft is capable of supporting and transporting strawberry plants enabling both the necessary upkeep and harvest. It integrates features often found in other productions like the flanges onto which the fruits rest. The gutters allow for the supply of nutrients to the plants and the usage of artificial lighting for the layers underneath. Air ventilation is also possible due to the spacing of the gutters and will be defined by the company in more detail. As these points state the essential need for plant cultivation this requirement is met.

   Also, as mentioned before, specific dimensioning of various parts cannot be permanently set since it differs per cultivar, therefore most variables that will differ per cultivation can be changed in the 3D model provided to Certhon like number of plants per meter, plant spacing, width height, etc. Thus, even if the system should be slightly adjusted there is the opportunity to do so by the company.

2. 90% plant space usage efficiency (m^3)

   A 90% space efficiency can be achieved by the system.

   All parts that surround the plant during cultivation fully contribute to its proper growth with the gutter supplying nutrients, the rafts providing support and the space around the plant which is needed for ventilation, growth and lighting. No space in the cultivation area is used solely for accessing or transporting the plants since this happens in a central hallway. The cultivation area itself is thus 100% cultivation space.

   The central hallway is the only part which is categorised as unused space with its sole purpose being transport and upkeep area. However, this area is relatively compact since only a few rafts have to be present in this area at a time as indicated by the transport method. This means only a width that is suitable for harvesting by labourers and transport to the opposite side is needed which could be around 3-5m wide. This means a facility with a footprint of 50x50m (0.25 hectare) a 90% space efficiency is achieved and thereby in line with the requirement.

3. 85% direct light on plants when mature

   At least 85% of the lighting efficiency is achieved. Although the precise lighting efficiency cannot be easily calculated this system is expected to be at least 85% light efficient due to the gutter spacing being at least as close as a case study done by Certhon. A closer spacing improves the lighting efficiency while the additional layers increase it even further due to the light having a chance of directly hitting the plants below.

4. Reduced or eliminated labour

   Reduced labour could be achieved and has been proven in studies that switched from manual labour to automated transport as described in the background. Since the transport mechanism still needs to be developed this requirement cannot yet be confirmed with certainty. However, the concept does make it possible for the harvest of longer chains of rafts which theoretically improves picking speed. Also there is a possibility of parallel integration of robotic harvesting. Therefore this requirement is expected to be highly plausible.

5. Opportunity for upkeep and maintenance of parts

   Parts of the system like the LED lights have a set lifespan and should be replaceable when the time comes. The high density of plants could interfere with the accessibility during cultivation and might lead to sacrifices of crops and yield during acute failure of parts. However, LED lights come with guaranteed performance and should be accessible during the cleaning stage of cultivation when no plants are present in the gutters and could be planned for. Also the raft quality can be checked during transport while the most mechanically complex part, the transport mechanism for upkeep and harvest, is by definition always accessible should it fail.

3.5.7 Recommendations and further improvements

Before implementing the system on a large scale there are various parts left to design and confirm. The main concern that needs to be worked on is ensuring that the plants will actually grow on the rafts in this setup. Strawberry plants grown using NFT requires sufficient root growth while the LED should not negatively influence the climate around the plant. Also the transportation mechanism of the rafts from one gutter to another should still be developed. A list of all next steps necessary to complete this project is stated in the appendix (see appendix 5.14 Further system improvements developments).

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5.2 Questions

Certhon representatives (R&D, Sales, etc.)
- What are the core values of Certhon?
Quality builds tailored to cultivators needs and location

- Main sources of income? (green house build projects, consultancy, maintenance, etc.)
90% greenhouses
10% climate-cells

- Which departments do you have?
Sales, r&d, calculations, finance, project execution.

- What are the primary activities of Certhon?
Develop and build greenhouses and climate-cells for cultivators, breeders and research

- How much competition is there in greenhouse solutions market? (Names/numbers)
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- Which stakeholders are present in the entire horticultural sector (self)?
Breeder, wholesale, cultivator, retailer

- Who are your customers (categories, names, numbers)?
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How are these customers found/acquired/contacted?
Who do you collaborate with?
What are these collaborations about?
What results have you gotten from these collaborations?
What is most important for your customer?
How much of these different stakeholders needs are being addressed by Certhon and their systems?
In what way will the future of food(production) develop in the next 10-20 years?
When looking at this business model canvas, what parts are missing, untrue or irrelevant?
What does the building process of a greenhouse look like?(steps on paper)
How big are the greenhouses/climate-cells that Certhon has built over the years? (size and shape)
- What is the cost of a greenhouse/m2? (kassenbouw afdeling)
€50-200 depends on lighting, cooling etc.
- How does height relate to cost?
See Certhon document provided (confidential)

- Cost of a climate-cell/m2
€400-800

- Which components go into the climate-cell/greenhouses?
See chapter 2.4.3 Climate-cell components

Lighting, cooling, heating, ventilation, air treatment, growing tables, substrates, irrigation, control room, plants, etc.

- How do these different components relate to each other in terms of pricing?
See Certhon document provided (confidential)

- How are research findings from external sources incorporated or used?
CONFIDENTIAL

- Which sensor are required for research in your climate-cell and which of them are also used in commercial settings?
Light, air temp, air humidity, pH, EC, amount of drain, substrate humidity, water temperature, outside temp humidity, CO_2,air volume passage, crop weight, irrigation quantity,

wishes related to sensors: crop size, colour, performance, weight plant/harvest, amount of flowers, shape, water samples,

- How are things like humidity, pH, temperature managed?
See above sensors mentioned

Cultivators (tomato, strawberries, block peper) (martin)
What does the process of cultivation look like(partial observation study)? How do you start a new batch? When and how often is maintenance required? How (often) are shipments to customers made?
Which (hand)tools are necessary for cultivation.

How do the operations differ per crop type?
What are your primary activities?
Which operations are least interesting to do?
Which are the simplest and toughest?
What do you value the most in your company?

What aspects of the process provides the most complications?
What are the costs of operation?
Can you draw out the cost division on your operation? (pie chart)
Where do you think you can save costs or labour?
How would you increase the yield of your operation?
What are the main limiting factors that could prevent you from upscaling?
Where do you get your seed(ling)?

What parts of the process would you like to see improved?
What parts of the system would you like to see improved?
Which parts are most critical in the system?

Wholesalers / Supermarkets
- How is quality maintained?
Checked visually and with tools / data input
- How much do you require/distribute each day?
25k per store
- What are the margins and what does it depend on?
Lucky with 2%

5.3 Cultivation additional information

Figure 77: Cultivation steps strawberries, paprika and tomato

Tomato

Common commercially grown tomato plants can grow up to 20m heigh and require more upkeep than other species like block peppers. Depending on the cultivator they start as either seeds or seedlings. Seeds are grown in germination chambers, since do not require a lot of space in the first weeks. They are transported to the gutters where they are spaced evenly and wound around a string to the ceiling (this is done to keep the plant growing upright). Every week the string is wound around the freshly grown top of the plant. The tomato plant tends to grow like a bush by nature, so any outgrowing leaves are pruned of in order to end up like two (one on each side) long vines. This long vine is placed alongside the gutter and runs around to the other side at the end of it. In commercial setups these gutters often stretch out for more than 100m. Sometimes the fruit bearing vines are shortened to end up with a set amount of tomato's per vine, in case the vine is left on for retail. These small tomato's ripen top down. During harvesting they are placed in plastic trays which are stacked and transported to either a packaging centre, distribution centre or directly to a supermarket.

Block pepper

Similarly to tomato's, block peppers are naturally bushy plants which require some pruning and stringing to end up with the common v-shaped long vines. Unlike tomato they do not need to be lowered and wound around the gutters, since they grow less high, do not bend as easily and do not require leaf trimming. However, this does make the process of harvesting less appealing because there are more bushes to search through.

Harvest house cultivation union

Processes fruits and vegetables from multiple cultivators like block-pepper, tomatoes, cucumber. Food arrives in a central hall and is sorted by quality and size after which it is packaged. Non satisfactory products containing scratches, dents or wrong colours and shapes are processed into sauces. This is only possible due to the size of the facility and the amount it processes.

5.4 Emerging problems global/local

The problem statement is derived from a multitude of problems that exist at various aspects of society. Solving the problem statement is one of many solutions which exist to tackle the bigger problems we face. The following list shows all the problems related to this assignment and thereby serve as considerations for the design phase. Since some are not self-explanatory they will be further elaborated further along in the text.

5.4.1 Global (Sustainable Development Goals of the United Nations)

1. Resource scarcity (water, land, food and fossil fuels)
2. Rise of population (nearing 10 billion by 2050)
3. Food dependency (urbanisation makes countries import dependent)
4. Climate change (disturbance in growing conditions)

5.4.2 Industry specific

1. Lack of labour (urbanisation)
2. Lack of expertise (ageing population)
3. Rising loans (bad in the sense that it increases production costs)
4. Overload of variables to manage for cultivator (environmental, biological and financial)
5. Highly competitive
6. Soil contamination / waste production
7. Automated systems currently in use are too large for vertical systems

5.4.3 Vertical plant factory / climate-cell

1. Initial costs (structure is as expensive)
2. Lighting costs (70-80% of electricity consumption)
3. Slower labour (Height increase)
4. Lack of cultivation knowledge on indoor cultivation (more research necessary)
5. Heat generated by LED
6. Light spectrum (Too flexible)
7. Data collection for production management
8. Space usage (safety and reachability)
9. Picking speed/cost
10. Algae growth
11. Plants are ‘unfit’
12. More light required for crop types 3 phases
13. Upkeep labour
14. Research centre…

5.5 Brainstorm sketches

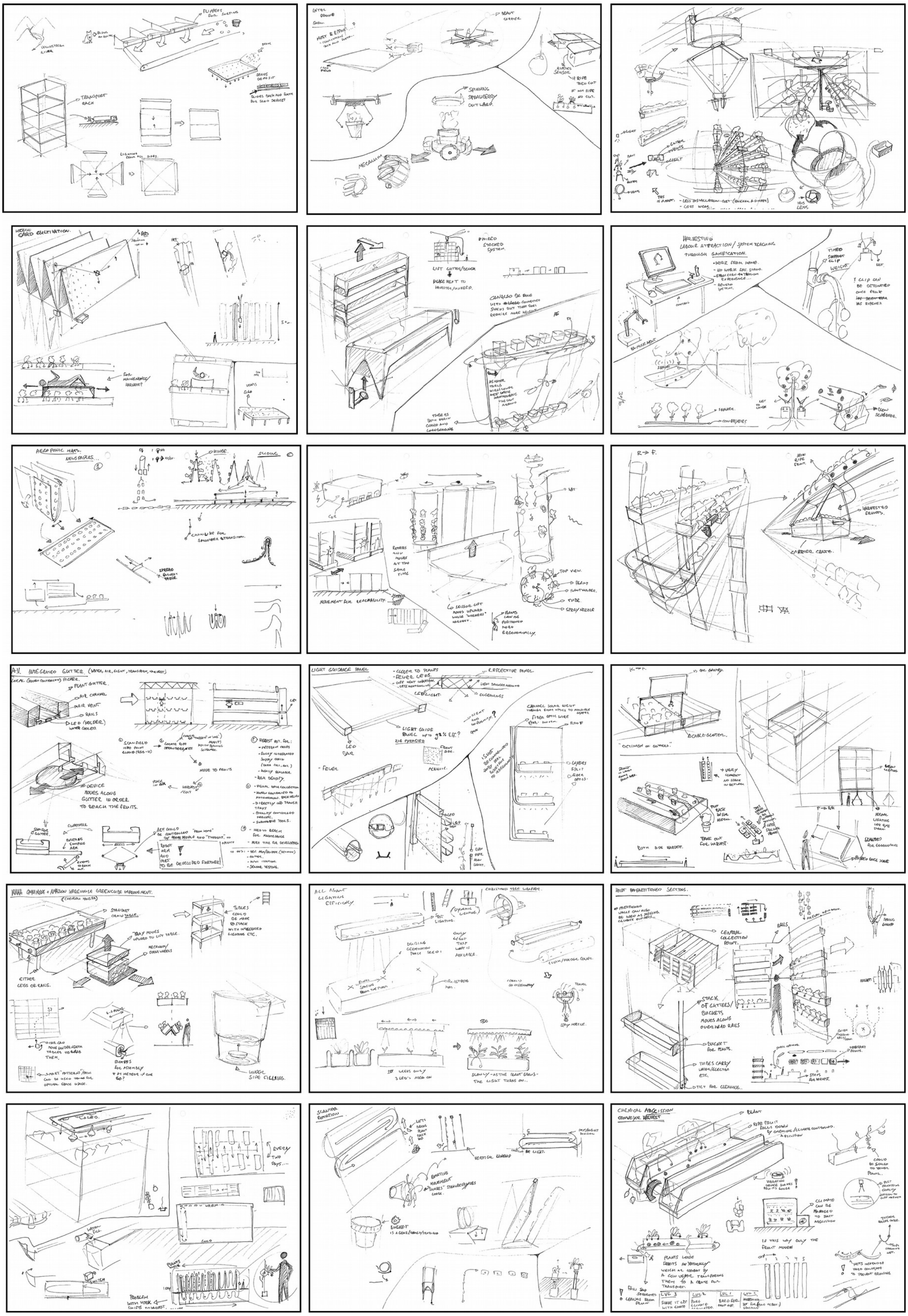

Figure 78: Collection of brainstorm sketches from the ideation phase

5.6 Morphological categories

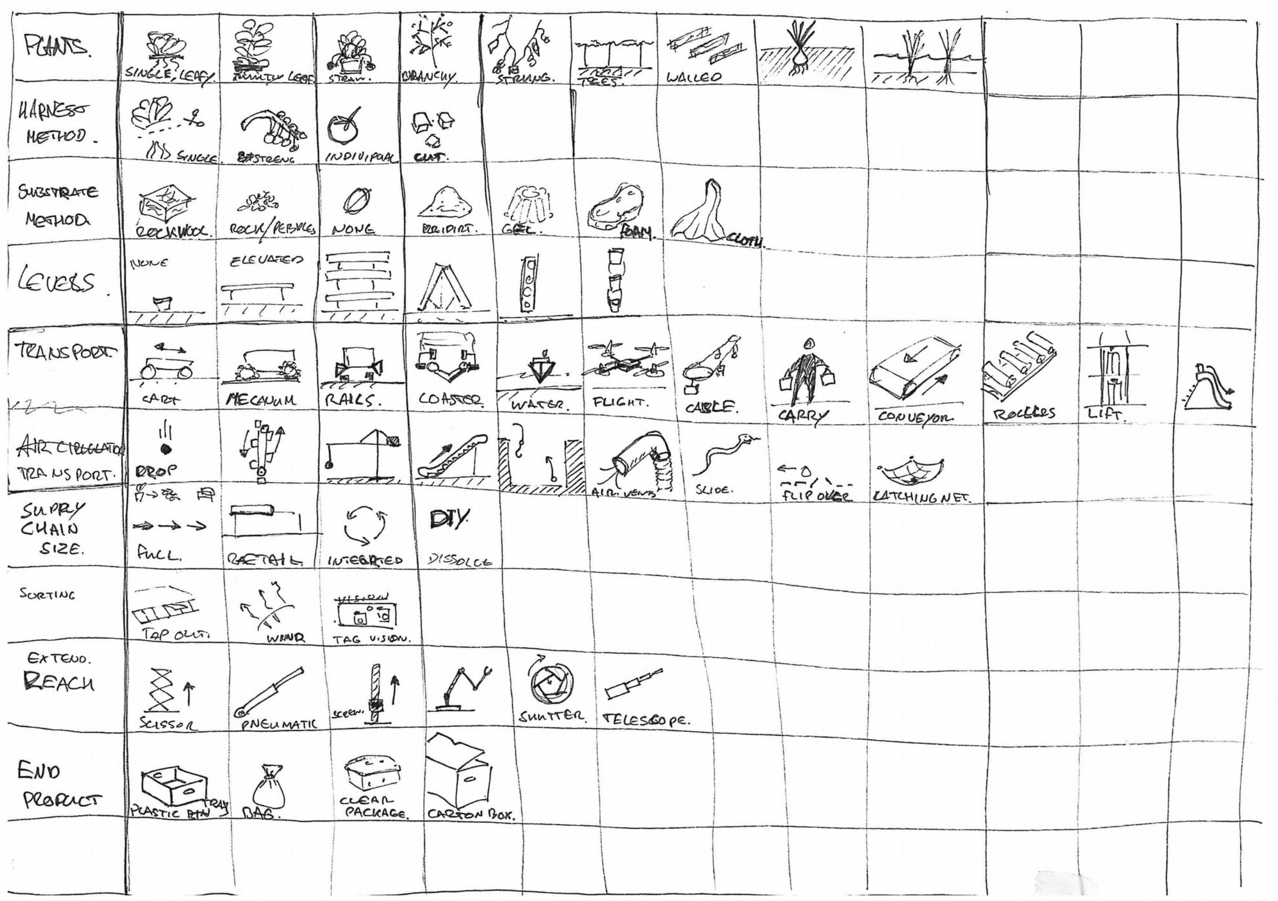

Figure 79: Morph Chart 1

From top to bottom in pictures:

Figure 79

- Plant type
- Harvest method
- Substrate
- Vertical tiers orientation
- Transport medium
- supply chain size
- Sorting of fruits
- Robotic arm reach extension
- End product shipping container

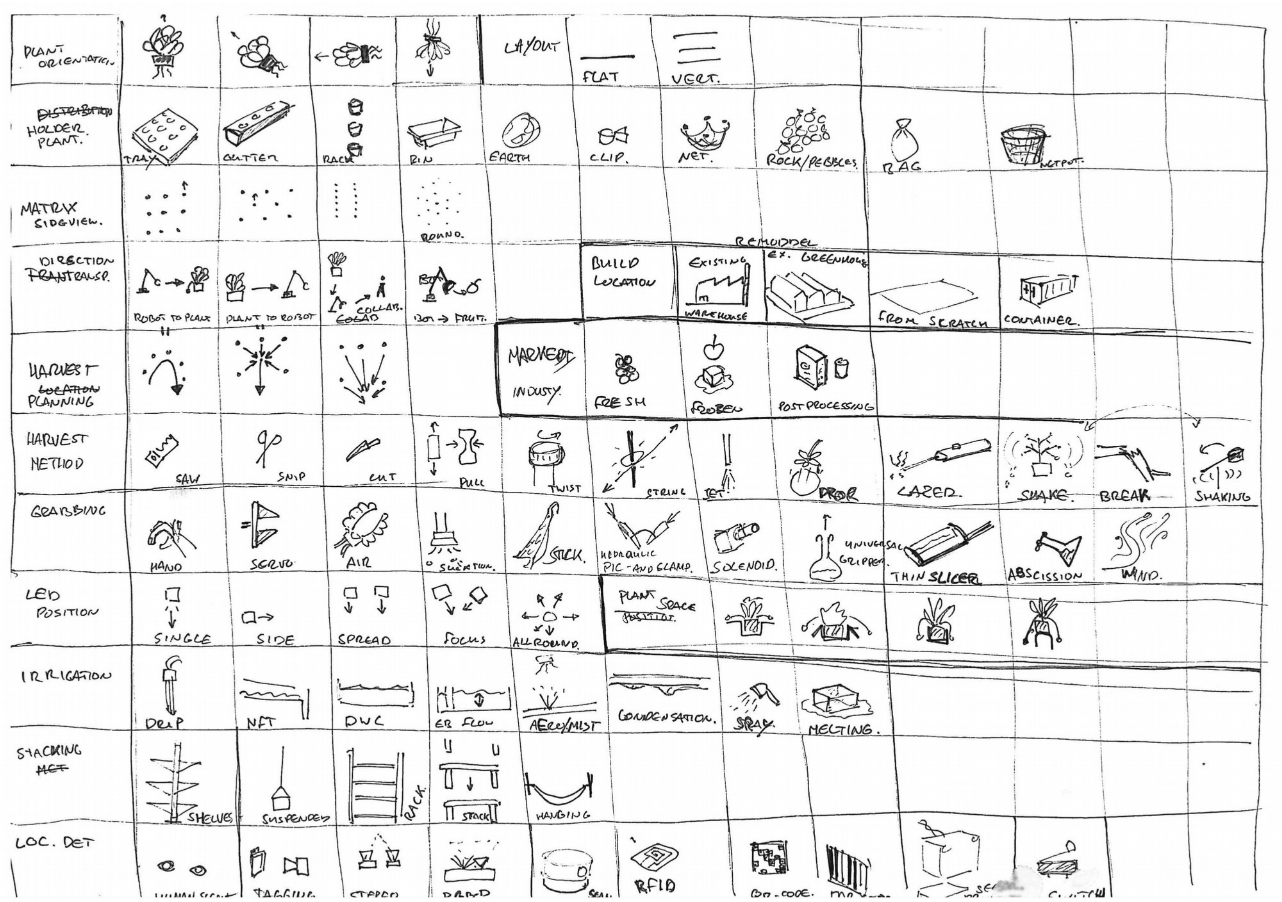

Figure 80: Morph Chart 2

Figure 80
- Plant orientation in field
- Holder of plant (or substrate carrier)
- Vertical matrix plane orientation
- Direction of transport (left) build location (right)
- Harvest transport planning (left) market (right)
- Havers methodologies
- grabbing of fruit method
- LED lighting position (left) plant gutter space (right)
- Irrigation method
- Stacking method
- Location detection for harvesting

5.7 Detailed requirements

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5.8 Detailed wishes

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5.9 Concept evaluation

5.9.1 Weighted objectives

		Development time low is bad	plants/m3 (high is good)	investment required vs. investment room	Weight moving parts	Light efficiency theoretical	Troubleshooting accessibility	Installation / manufacturing simplification	Usability (harvest, maintenance)	Plant knowledge	Safety laws	Future implications	total	certainty	coolness	total	**P**	**M**	**I**
Name(descriptive)	Development timeline	15	25	25	5	25	10	5	5	5	10	10	**140**						
Gutter robots	walk/work in between – human controlled/collaboration bot high density – full auto high density – transfer to different plants	5	8	5	6	8	2	6	7	10	10	10	965	50.00%	9.00	4343	Highest potential to be the future of autonomous high density. No moving parts / additional stress on plants during production	Takes time and effort to develop	Interesting way of dealing with 100% autonomy issue. Could be done parallel to or in collaboration with robotics
Gutter transport		7	10	4	5	8	2	5	10	10	10	8	1005	80.00%	7.00	5628		principles proved to be too expensive	
Vertical walls	Test vertical growth lighting in between the crops – test different person moving devices -	7	9	8	9	8	10	8	9	2	5	8	1100	80.00%	7.50	6600	Easy, quick and cheap solution to issue of space efficiency and reachability in a vertical setup	Problems with safety and plant orientation	use of aeroponics allows for higher control.
Wall transport		7	9	5	3	8	6	3	9	9	8	8	995	60.00%	8.00	4776	Integrate vertical structure in movement		
Plant transport		8	8	6	7	8	2	6	9	10	10	8	1030	70.00%	7.00	5047	Stationary gutters, so fewer big parts to move	- unsure how plant transfer happens	

Figure 81: Weighted objectives criteria and valuation

5.9.2 Post concept decision considerations

- What size, material and manufacturing process of the products
- how do they function
- how much flow is necessary.

Raft detailing
- push pull force
- buoyancy
- flow
- workings
- What type of material raft?

needs to float, be impact resistant, not water absorbent, cheap, hold numerous plants, clearance for plants

- What kind of shape raft?

carried by water, not tip over, not get stuck, easily cleaned and used

- What kind of shape gutter?

Integrate all functionalities, one extrusion, watertight, LED location (in the middle due to costs),
What type irrigation interval and speed water flow?
Enough to provide nutrients to plant, to cool the LEDS and to float the rafts

- suspension interval
- movement actuator
- LED fixture
- air ventilation
- labour working speed / plant availability
- cleaning operations

Transport rotation action
- plant placement
- speed of the mechanism
- ease of access and usability

5.10 Calculations

The graphs shown below are made using an excel sheet which shall be handed aside from the report. Using this excel sheet one can get a better understanding of the calculations made (like what influences what) and change parameters (often indicated in yellow) to see further influences.

5.10.1 Area per crop

	Production volume total (kg)	Area total (m2)	Average production (kg/m2)	Quantity consumed in The Netherlands (kg)	Total area required Dutch consumers (m2)	Retail production area (m2)	Possible chamber dimensions (m)
Cucumber	160000000	2250000	71.1111111	85000000	1195312.5	199.2	10x2
Block-pepper	325000000	12440000	26.1254019	38000000	1454523.077	242.4	10x25

Figure 82: Area per crop calculation (cucumber and block-pepper)

Figure 82 shows the area required per store for the production of cucumber and block-pepper.

5.10.2 Cost production strawberry

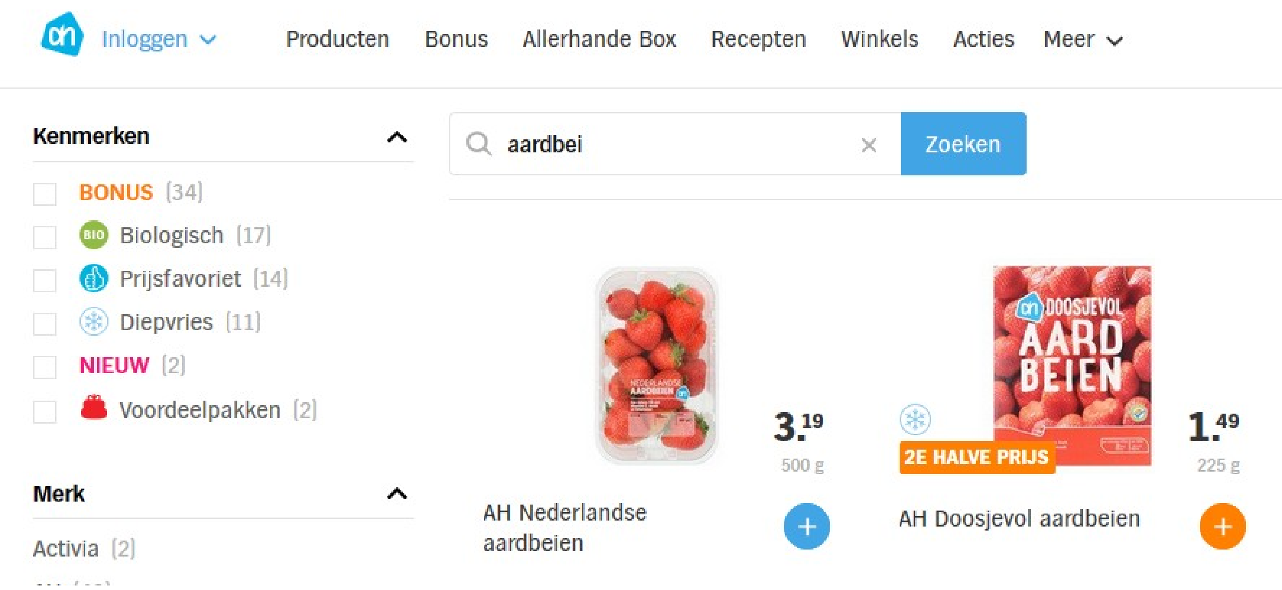

Figure 83: Screenshot Dutch retail website with the price of strawberry in 2019 (Albert Heijn)

Certhon provided sheets on strawberry climate-cell production resulted in a price per kg of strawberry of €2,31 to €5,20. Retail price of strawberry is currently around €6,- per kg (Figure 83).

5.10.3 Labour cost

General			Robot			Labourer		Labour speed up
strawberry kg yield per m2 per year	1.5625		Seconds per strawberry	30		€/kg	€ 0.60	€ 0.48
						€/h	€ 15.00	€ 15.00
Weight per strawberry	0.03		strawberries per second	0.033333		Strawberries per second		
strawberries per plant	52.083333333333		strawberries per day	2880		strawberries per day (8hours)	6666.66666666667	€ 8,333.33
			Meter strawberries / d	1261.44		Meter strawberries / d	2920	€ 3,650.00
strawberries per m gutter total	833.33333333333		Harvest accuracy	80.00%				
			Kg/u			Kg/h	25	€ 31.25
strawberries per m gutter average per day	2.283		Kg/d (24 hours)	69.12		Kg/d (8 hours)	200	€ 250.00
			Costs as labour	€ 41.47				
			Costs as labour fast	€ 33.18		Cost per meter/d	€ 0.0411	€ 0.0329
Min wage (€/h)	€ 15.00							
Depreciation(years)	7							
Plants per m	16	(2 cycles)						
Gutters per m2								
Picking speed improvement	125.00%	(max 25)						
	Normal	**Sped up**						
Difference (bots/human)	2.89	3.62						
Cost bot/year	€ 15,137.28	€ 12,109.82				**Saving per m/y**	€ 3.00	
Investment Space/bot	€ 105,960.96	€ 84,768.77						
Investment space /labourer	€ 306,600	€ 306,600						
Labour / hectare	3.4246575342466	2.7397260274				Investment space/m	€ 21.00	
Investment(savings) / hectare	€ 1,050,000	€ 840,000				**Investment (savings) /hectare**	€ 210,000.00	
Normal vs. full auto	Transport vs. full	Transport vs. no transport						
							Improved labour (25% faste	Normal labour
						Labourer	€ 120,000	€ 30,000

Figure 84: Labour costs and robotic investment space calculation

Figure 84 shows the calculations and data required to calculate labour costs. The yellow parts can be adjusted to specific cases. The data is generated from the a picking speed of 25kg per hour and the yield per plant which is derived from data provided by Certhon. The cost savings in grey indicate how much money is saved in the different situations (a sped up workforce and a roboticised one).

5.10.4 Vertical layers

	Costs per m2								Costs TopLED			€ 293.75	
Venlo Climate cell	€ 275.00				← add land value for shift of line				Number of LED per m2 (umol)			0.56452	
Additional height costs factor	1				← the higher the structure the more this becomes				Lighting efficiency %			85.00%	
Gutter + irrigation / meter	€ 59.05								Led per m gutter			€ 195.09	
Additional layer cost factor	1.10	1.20	1.30										
	€ 5.91	€ 11.81	€ 17.72		← max additional cost first layer to satisfy factor								
									Plants per m gutter			16	2 per year
									Plant cost			€ 0.50	
Gutters per meter	2.00	2.00	2.00						Plant costs per m gutter			€ 8.00	
									Kg yield per plant			1.375	
Final costs per m gutter	gutters/m	Floors	Costs per m gutter			Costs per m2	**Investment (savings)/m2**	Yield per m2 (kg/y)	costs per kg (without HVAC and electronics)				
	2	0	€ 399.64	€ 399.64	€ 399.64	€ 799.28	€ 799.28	44	€ 9.08				
	4	1	€ 336.80	€ 342.70	€ 348.61	€ 1,347.19	€ 1,849.95	88	€ 3.83				
	6	2	€ 320.38	€ 333.96	€ 348.72	€ 1,922.25	€ 2,873.44	132	€ 2.43				
	8	3	€ 316.06	€ 339.51	€ 367.20	€ 2,528.50	€ 3,865.76	176	€ 1.80				
	10	4	€ 317.05	€ 353.04	€ 399.25	€ 3,170.47	€ 4,822.36	220	€ 1.44				
	12	5	€ 321.11	€ 372.95	€ 445.26	€ 3,853.31	€ 5,738.08	264	€ 1.22				
The cell should be higher (more expen	14	6	€ 327.35	€ 399.06	€ 507.76	€ 4,582.84	€ 6,607.12	308	€ 1.06				
	16	7	€ 335.35	€ 431.87	€ 590.82	€ 5,365.63	€ 7,422.90	352	€ 0.95				
	18	8	€ 344.95	€ 472.28	€ 700.07	€ 6,209.09	€ 8,178.00	396	€ 0.87				
	20	9	€ 356.08	€ 521.53	€ 843.05	€ 7,121.60	€ 8,864.06	440	€ 0.81				
	22	10	€ 368.75	€ 581.22	€ 1,029.66	€ 8,112.59	€ 9,471.64	484	€ 0.76				
	24	11	€ 383.03	€ 653.30	€ 1,272.84	€ 9,192.69	€ 9,990.10	528	€ 0.73				
	26	12	€ 399.00	€ 740.17	€ 1,589.45	€ 10,373.88	€ 10,407.48	572	€ 0.70				
	28	13	€ 416.77	€ 844.72	€ 2,001.43	€ 11,669.63	€ 10,710.29	616	€ 0.68				

Figure 85: Vertical layer costs calculation per meter gutter

Vertical layer costs are calculated in a way in which the costs of the structure is divided in a way which eventually resembles the costs per meter gutter. The different costs per meter gutter in different situations (costs, height efficiency, etc.) can then be compared.

5.10.5 Pallet rack structure

	width (m)	Height (m)	Depth (m)	area (m2)	Number of layers (minus floor)	Number of sections	pallet price
Pallet	11.00	6.00	1.10	12.1	3	3	€ 1,065.00
	per section	per beam pair	total				
Load capacity (kg)	15800	3300	45000				
safety factor	1.4						
price (m2)	€ 88.02						
price per layer (m2)	€ 29.34						
load capacity per layer (kg)	900						
Gutter weight (kg)	25						
gutter weight safety factor	3						
Minimum spacing gutter (m)	4						
Rack spacing (m)	12						
Price per layer with gutter spacing	€ 7.33						
Price per layer with rack spacing	€ 2.44						

Figure 86: Pallet rack costs per gutter layer calculation (Begra Magazijninrichting BV, 2019)

The calculations for the costs of additional layers is calculated using traditional pallet racks. Here the price per square meter is determined at €88. However, the capacity of these racks is 45000kg over 12 m^2 which far exceeds the maximum weight per meter gutter, multiple safety factors are included to account for possible variations in weight and capacity. Thus a certain spacing can be applied so there are pallet rack every 4-5 meters. The spacing can be calculated using a weight factor (for safety) and the maximum suspension distance for a gutter (the latter being the limiting value). The minimum gutter spacing is 4 meter and the maximum rack spacing is 12. The resulting price per meter gutter over these layers is thus €7,33 and €2,44 of the gutter and capacity spacing respectively. Any additional cost for installation is quite low and is assumed to be no more than 10% of the cost price.

5.10.6 Day night cycle costs

LED			cycle	Normal 16	Day/night		
Lifespan Hours	36000		day usage	16	24		
Cost/m	€ 293.75		lifespan (y)	6.164383562	4.109589041	kWh/y	1006.9
Lifetime factor	1		Amount needed	1	0.667	€/kWh	0.05
Wattage/m	172.4137931		Effective investment costs/y	€ 47.65	€ 47.65	Running cost/year	€ 50.34
Lighting efficiency	70.00%						

Figure 87: Lighting costs day night cycle versus day night chambers

The use of day and night cycle chamber calculation is shown in figure 87. Here the investment costs as well as the lifespan are most important. This calculation shows that it does not matter whether one uses day and night chambers or cycles, the end result is the same since the lighting needs to be replaced after a certain period of use (here 36000 hours as indicated by Phillips lighting).

5.10.7 Raft Calculations

Buoyancy

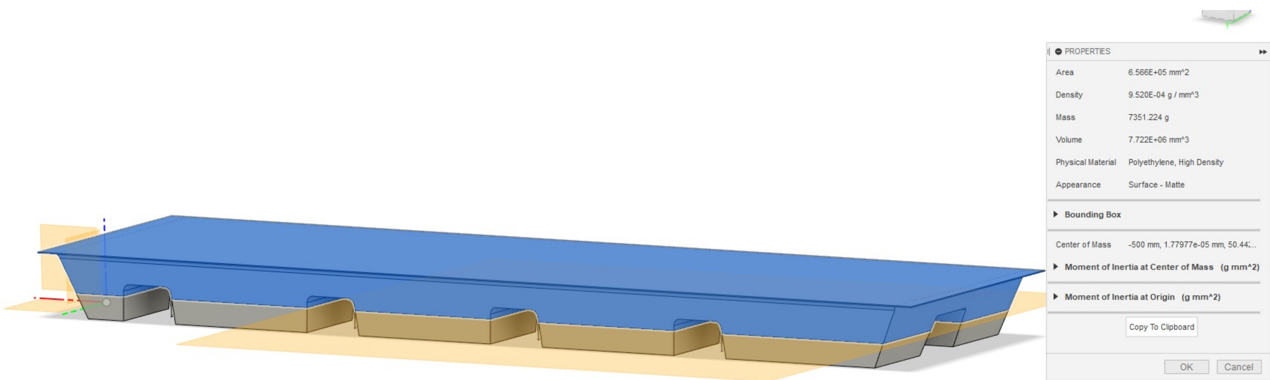

Figure 88: Sample image method to calculate displaced volume at different heights

The buoyancy is determined from the 3D models made using fusion 360 (figure 88). The models could be split into separate bodies after which the volume of the split body could be determined by the program. Note that the model is a solid and not hollow to account for the volume inside the raft, otherwise only the volume of the thin wall was calculated. Figure 89 shows the different displaced volumes at different heights, i.e. if the raft is submerged for 20mm it will displace 1.7L.

Raft specifications	
Height at volume (mm)	displaced volume (L)
20	1.7
25	2.3
30	3
40	4.4

Figure 89: Different displayed volumes of model

With the following information:

Plant weight strawberry: 300grams

8 plants per meter: 2.4Kg

Weight raft (1m): 0.5-1Kg

Total weight: 3.1-3.6Kg

The raft can support the plant weight and thus around 40mm of water should be available in the tank.

Push/pull force

The force required to push or pull a row of plants around 100 meter long is determined by measuring the force required to push a certain raft with a set length and weight. This force is then multiplied by the amount of rafts that would fit the 100m together with a safety factor.

The measured force required to push a raft with a 3 plant load on water was less then 0.1 Newton. Per meter this would mean roughly .2-.3N. With a safety factor of 2 this would come down to 0.5N per meter force required. So for the system to push or pull a row of 100m it would require to displace 50N or around 5.1Kg.

5.10.8 LED Calculations

Heat transfer and required cooling

The calculations and test performed to measure heat absorption by the water are shown here. This is required to calculate the amount of water flow needed in the system

Energy required to heat 1L of water 1°C: 4186 Joule

Lamp power (W)	Electric efficiency (%)	Heat to cool (W)	Water temperature start (°C)	Water temp end (°C)	Water volume (L)	time (min)	Heat capacity J/(kg.K)	Absorbed heat (W)	Absorbed heat(%)
110.2	38.8%	57.2	20.2	27.6	6.0	110	4186	28.2	49.2%

Time (min)	temperature (°C)	heat absorbed(%)
0	20.2	
3	20.3	14.0
7	20.7	41.9
10	20.7	0.0
15	20.9	16.7
20	23.8	242.8
47	24.7	14.0
72	26.7	33.5
82	26.8	4.2
110	27.6	12.0
		42.1

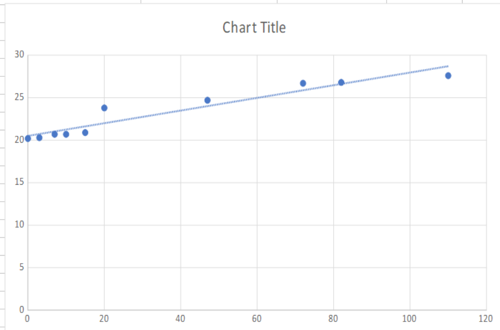

Figure 90: Water LED Heat absorption over time

Figure 90 shows heat absorption measurement over time which comes down to around 40% in the most simple setup and is thus expected to be sufficient enough.

5.10.9 Air duct

The information used is derived from the KWIN 2019 (Raaphorst & Benninga, 2019), since the price of the components is conveniently displayed in €/m.

gutter: 5,5€ per meter, lasts 8 years, so €0,70 per meter per year

plastic air duct: €0,15 per meter but replaced every year with installation and removal costs (taken at 10min/100 meters), with loan calculated at €15,- / 600 = 2.5cents per meter per year.

These calculations show that the costs of the plastic air ducts are far lower that any integration into the gutter even when considering labour. The costs for installation and yearly replacement for integrating the air circulation vents into the gutter is not considered to be a viable option (too expensive). Perhaps when the vents provide additional load capacity that reduce other costs it could be interesting to look into.

5.11 Prototyping

Figure 91: MARTENS gutter (‘MARTENS Bakgoot 125 mm grijs, lengte 2000 mm’, n.d.) *with end-cap and drain. And ball valve connected to the drain.*

The parts required to perform the tests are as follows

Raft design

- Standard gutter (GM-19, A:130,B:40) 5-10m long, 1-3x? Height?
    - First simple roof gutter
- Front back plate for eb-flood / NFT
- Styrofoam blocks material (lightweight and stiff)
- prototypes of rafts
- Cutting supplies
- Glue
- irrigation
    - Tubes
    - Pumps
    - water
- Adjustable pillars for flow of water)
- Plants (weights or something similar)

- Cups
- sensor
    - flow sensor
    - force (newton meter)

Initial trial results:

- works and floats

- can hold significant weight

- water drainage is troublesome, not everything clears, but this can be a benefit since water could be cooling

- expansion to the sides when holding large quantity of water

- prone to tilting with narrow and high load, design should prevent that

- high friction when not submerged

- pulls raft when draining

- water could be driving force, drift already visible when draining and at higher water flow. Flow speed sensor/regulator needed.

Vacuum forming samples (see figure 92)

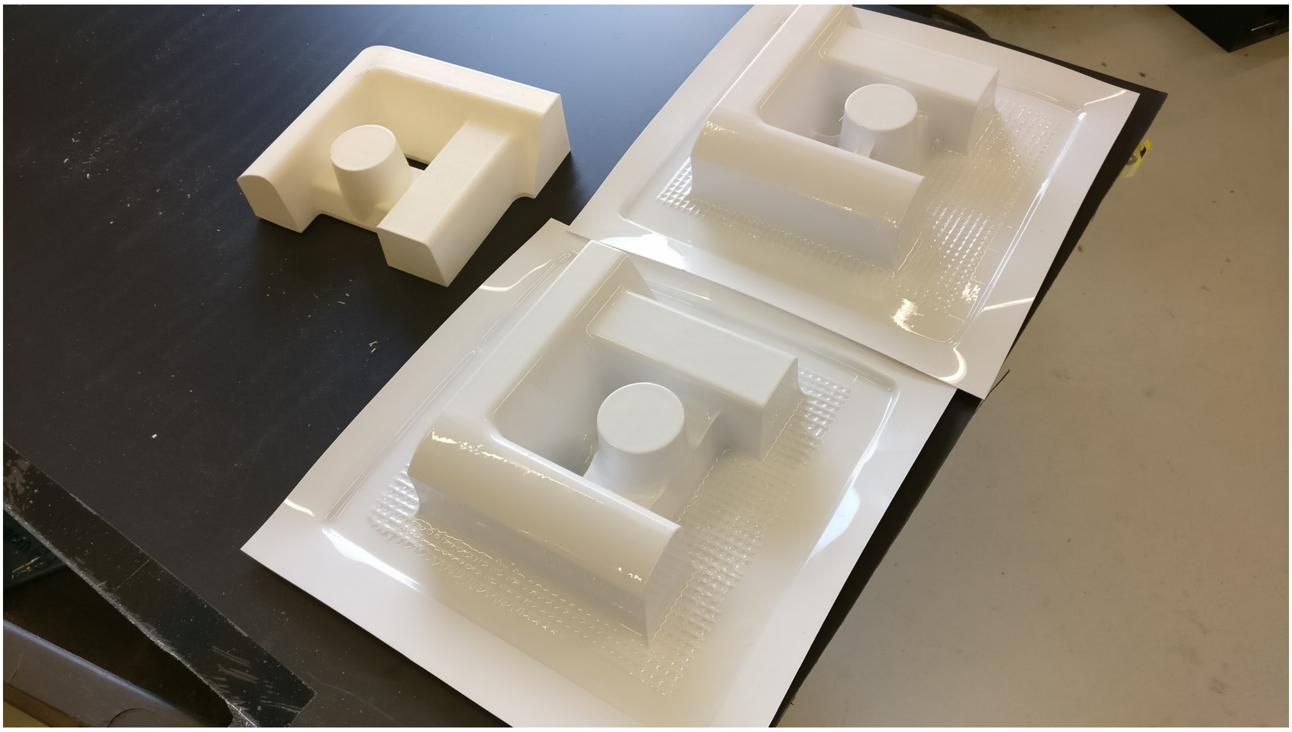

Figure 92: Vacuum formed test samples

LED heating

- Gutter
- End-caps to seal the gutter
- water
- Spare LED strip
- Sensors
  - Heat
  - timer

5.11.1 Manufacturing companies

Raft

Dutch manufacturers and prototyping companies capable of making rafts

batelaan
https://www.batelaan.nl/technieken/vacuumvormen/

thermoforming
https://www.thermoforming.nl/vacuumvormen

dimarco
https://www.dimarco.nl/

vink kustoffen
https://www.vinkkunststoffen.nl/toepassingen/verpakking-labels/special-products-projects

plastica
https://plastica-thermoforming.eu/technieken/vacuumvormen/

beekenkamp
https://www.beekenkamp.nl/verpakkingen/productie/

Later parts can/should be manufactured using the injection moulding process since it is faster, cheaper at higher volumes, more flexibility on the designed, little to no finishing and less waste

Gutter

Gutters can be manufactured by meteor systems

structure

Pallet rack structures can be bought from:

Berga

https://www.begra.nl/

pallet stelling.nl
https://palletstelling.nl/

5.12 Details raft versions

CONFIDENTIAL

5.13 Final concept benefits

CONFIDENTIAL

5.14 Further system improvements developments

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