Hybrid Urban Vertical Farming

by

K. P. Verbraeken

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first mentor
Ir. A.C. Bergsma
Architectural Engineering & Technology
TU Delft

second mentor
Dr. A.J. Jenkins
Environmental & Climate Design
TU Delft

front matter

“For the more than one billion people who, through no fault of their own, go to sleep hungry each night; and for the three billion more who will most likely arrive on this planet over the next forty years to join them in their suffering, if nothing changes.”

(Despommier, 2010)

preface

a word from the author

I am a Westlander, and when young Westlanders want to earn money, they work in greenhouses. Set your alarm at six, start work at seven and have a bakkie pleur at ten. Plukkie al? Ja, blad. Since I was twelve.

When I started my bachelor's in 2018, my interest in steel structures arose, and over the years that I worked in the sector I met growers who had their greenhouse demolished. Some build a larger one elsewhere to remain competitive, others made space for urbanization. To my surprise, none considered to reuse the steel structure; they discarded it as scrap metal; *trend 1*. Another trend, which I discovered during a bachelor's course, is a looming food shortage. The population is expected to exceed 10 billion by 2050; *trend 2*. However, current farming practices are insufficient to feed that many due to their inefficient use of farmland. Scaling up isn't the solution since farmland is limited. In fact, current farmland is shrinking due to depletion caused by plough-based open-field cultivation that accounts for 85% of global crop production; *trend 3*. A solution is sought in Westland, which is an area of horticultural specialization that cooperates with companies worldwide to develop farming practices that maximize crop yields per square meter farmland: vertical farming. Although vertical farming produces superior quality crops, their energy consumption is a problem. Its production relies on artificial lighting, which requires lots of electricity, making it commercially uncompetitive. Therefore, it is not (yet) a suitable alternative for efficient farming in 2050; *trend 4*.

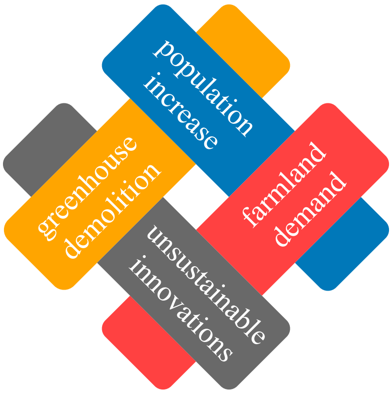

figure a: overlap of trends (own, 2023)

Four trends and one problem: a looming food threat. Sounds like an interesting topic for a thesis. But I knew myself, I tend to lose interest in academic projects after a week or ten. Therefore, I had to pick a graduation studio that aligned with my personal interests. And as I knew that the lifespan of steel exceeds the age of many greenhouses that are being demolished today for one of two reasons, the research fits seamlessly with the graduation studio *reuse of existing structures* - within which I could link reuse to a global problem. Rather than viewing trends as separate problems, I saw opportunities that overlap and can be combined to find a space-efficient way of growing crops by 2050 (*figure a*). This thesis describes the journey of that exploration; from apersonal interest to an academic research.

Enjoy reading,
Koen Verbraeken.

acknowledgments

a word of thanks

Throughout my graduation, I have received information, help, interest, guidance, support, tips, and motivation from mentors at Delft University of Technology, my workplace VB, and a range of companies in the horticultural sector. I would like to take a moment before the start of the research to thank them.

I would like to thank my mentors for their guidance throughout my graduation. My first mentor, *Ir. A.C. Bergsma* (Architectural Engineering & Technology), has been invaluable with his enthusiasm for my research, his critical questions, and his desire to expand my thesis beyond just a design. My second mentor, *Dr. A.J. Jenkins* (Environmental & Climate Design), has been a source of support with his inexhaustible knowledge in the field of urban agriculture, his guidance in conducting analyses and optimizations, and his emphasis on the importance of a narrative that engages listeners and avoids confusion. Thank you.

I would like to thank my source of practical knowledge, VB, where for thirty weeks I had the privilege of accessing the expertise of employees for information that is not available online. *Edward Verbakel* (CEO), for welcoming me into your company and your interest in my research. *Marco de Bruijne* (operational director), for giving a student with his own research an opportunity. *Frank van Veen* (operational manager horti), for helping to make my design as practice-tested as I desired by connecting me with VB's partners, and thank you for your (successful) attempts to jump scare me along the way. *Marcel van Leeuwen*, *Thomas van der Knijff* and *Daan Salters* (engineering horti), for always making time to answer my questions and creating the nicest office environment I could have asked for, without you three I would been lost months ago. *Roebi Weterings* (strategic organisation manager), for the effort you have made to ensure that I feel at home at VB. *Arnaud Blom* (quality coordinator), for your interest, motivation, and inspiration from a research and development perspective. And at last, *Patrick Polderman de Jong* (calculation), for helping me clear my head in breaks, unfortunately by beating me time and again at the pool table.

I would like to thank those whom I spoke with that work in companies in the horticultural sector with whom I came into contact through VB:

Arend van der Knijff [van der Knijff] for his knowledge on the reuse of greenhouse components, *Rudy van den Berg* and *Marco van der Velden* [Artechno], for their knowledge on providing crops with resources in a vertical farm, *Robbin Duijnisveld* [Duijnisveld], for his knowledge on steel production and reuse, *Koos van der Ende* [BOAL], for his knowledge on aluminium production and reuse, *Bart van Meurs* [Koppert Cress], for his knowledge on growing microgreens and providing crops with resources, *Emiel Moor* [Sion Orchids], his for knowledge on the crop density of a two-layer greenhouse, and at last *Renate Bouwhuis* [Poedercoat Westland], for her knowledge on reflective coatings. Thank you all for your generosity.

I want to thank my friends, whom I have seen too little during the course of my graduation, but who were always there when I needed a moment to think about something other than my research.

And finally, I want to thank my parents, who were interested during calm weeks, but above all accepted and endured my stressed and grumpy mood during stressful weeks.

Thank you all.

summary

abstract

As a solution to declining availability of famland and as an alternative to unsustainable vertical farming, this thesis proposes a new farming practice: hybrid urban vertical farming. It has a high footprint utilization and combines vertical farming with daylight utilization. This is a summary of the research and results.

This research begins with the problem statement: food securtiy is in jeopardy by 2050. By then, there will be 10 billion people on earth while the area of farmland is shrinking. Conventional farming practices use too much space per crop, and thus cannot be scaled up to produce more crops. The alternative that uses farmland more efficiently, vertical farming, is not sustainable enough to be a globally commercially interesting alternative. Therefore, a more sustainable alternative is needed to sustainably grow a lot of food on a small footprint in the years up to and beyond 2050. The proposal is hybrid urban vertical farming: a new farming practice that reuses greenhouse components to build a modular construction in which layered growing systems can be built that can also utilize daylight through the glass greenhouse deck. This way, its sustainability over vertical farming is increased through material reuse and artificial light reduction.

The research continues with an examination of the components that compose greenhouses, and an analysis of how those can be refurbished reused. This was done in close collaboration with companies in the sector. With that knowledge, a case study greenhouse, MightyVine phase 3 from Chicaco, the United States of America, is then analyzed. Using the resulting components, nine modules are designed that together can create any possible module configurations to withstand wind loads. A sliding and rotating growing system is designed for in those modules. Those features contribute, respectively, to an even exposure to daylight for crops in different containers, and to reducing the footprint occupied by workspace. Building modules with reused components results in as much as 45-76% of the carbon footprint being saved. For the growing systems, which reuse midfield columns for their structure, it is 16-18%.

With the design of growing systems completed, it was optimized how far they need to be spaced apart to maximize the use of daylight on a given footprint. This revealed that growing systems must be side-by-side to naturally provide 34% of the light requirements of crops annually. Knowing that, it was also possible to determine the module configuration that reuses the most midfield columns (which is the most reused greenhouse component). That optimal module configuration is eight modules long and four modules deep. This leads to a 95% reuse rate for midfield columns. That module configuration can grow 3.3 times more crops per square meter than the case study greenhouse, and at only 4.5% of the greenhouse's footprint.

Carbon footprint calculations that consider only the emissions emitted in the production of materials for module construction and growing systems show that hybrid urban vertical farming is less sustainable than greenhouse agriculture: by a factor of 1.63 times. Published research indicates that vertical farming is 2.4 times less sustainable than greenhouse agriculture. So the conclusion of this thesis: a hybrid urban vertical farm truly is a *hybrid* farming practice. It has a better footprint utilization than greenhouse agriculture has, but it is less sustainable. However, it is more sustainable than vertical farming. So, today, hybrid urban vertical farming is not yet the most sustainable farming practice out there, but when farmland runs out in the years to 2050, then hybrid urban vertical farming will be the more sustainable option over vertical farming. Until then, the concept can be further developed and made more sustainable to be competitive with conventional farming practices sooner if possible.

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figures

Figures are numbered sequentially in this thesis, alphabetically in the front matter, numerically in the main research. Figures in the appendix are numbered separately per appendix.

tables and graphs

Tables and graphs are numbered sequentially in this thesis. Tables in the appendix are numbered separately per appendix.

part one

intro

p1 intro

in this part

To start research, it is necessary to clarify the impetus. What problem initiates the need for research, and how do questions and methods arise from it? That is covered in p1 intro.

The introduction is composed of three chapters: first, c1 food threats describes why the way crops are cultivated today will not allow humanity to produce enough to feed the population by 2050. Second, c2 the sector explores the current state of the horticultural sector and the existing farming practices. How do those practices work, and why do they not perform well/sustainable enough? And most important, how can their strong features be integrated into an innovative farming practice that can fill the sector's gap, whilst omitting as many bad features as possible that render the current ones unsuitable for future crop production. Third, the conclusions from the first chapters are turned into a description of the research topic in this thesis in c3 research.

After the introductory part, the actual research starts. The first two chapters of this part already refer to subsequent parts, in which knowledge gained is integrated in the design.

c1 **food threats**

c2 **the sector**

c3 **research**

c1

food threats

in this chapter

Today, in some parts of the world, feeding everyone is already a major challenge. Largely because of the Earth's increasing overpopulation and accompanying urbanization, and six other so-called food threats (trends that threaten producing enough crops for 10 billion people), food security is in jeopardy by 2050. These food threats are discussed.

population and urbanization

Currently, on May 30th, 2023, Earth is populated by 8,035,916,351 people (about eight billion), and it is a general consensus that the planet is overpopulated. However, the end is not yet in sight, the most recent projections predict that the population will grow to 8.5 billion by 2030, and to 9.7 billion by 2050 (United Nations, 2022a). At the same time, prosperity is increasing due to the rise of developing countries. This means that by 2050, not only will there be 1.7 billion new mouths to feed, but the existing eight billion will want to be fed more. In a best-case scenario, this leads to a 60% increase in global crop demand. Less favorable predictions about population, income and diets push the increased demand much further (Alexandrator & Bruinsma, 2012). To produce 60% more crops by 2050, the crop cultivation sector must grow by 1.3% annually, and since growth between 1962-2007 was 2%, the goal seems attainable. However, this first food thread, and those that follow, make for a great challenge to achieve 1.3% annual growth for 27 years (Fisher et al, 2014).

Today's 8 billion and 2050's 9.7 billion must live somewhere, and as 80% of gross domestic product is generated in cities; many try their luck there and move away from rural areas. This shift of residence is called urbanization, and has been an increasing trend since the industrial revolution. Today 56% lives in cities, by 2050, the urban population will be 70% (United Nations, 2019). Urbanization is accompanied by a shift in lifestyle and diet; demand for grains and staple crops is replaced by a demand for fruits and vegetables. While the rich will enjoy the prosperity of the city, the majority of the poor will still live in rural areas, and remain part of the (growing) one billion that cannot meet their basic food needs.

decrease in farmland

With the demand for crops increasing by 60%, it seems logical to scale-up the current way of food production by 60%. Unfortunately, this is impossible. Today, 95% of all crops are grown in a one-layer soil-based system: *open field farming*. For that, farmland the size of South America is used. To grow 60% more crops this way would require farmland the size of Brazil, which is not available anymore (Despommier, 2010). More worryingly, however, is that the total amount of existing farmland is shrinking due to three factors.

First, urban sprawl often occurs on farmland; studies indicate that 1.8% of the world's farmland will be reclaimed by expanding cities by 2030 already. Much of this reclaimed land is currently part of the world's most efficient farmland that is up to 1.77 times more productive than the global farmland productivity average; thus the losses are significant (Bren d'Amour et al, 2017). Second, today's plow and fertilizer-based agriculture is rapidly depleting soil: every minute thirty soccer fields of farmland are being depleted (Mongomery, 2007). Third, climate change causes temperature increases, changed precipitation paterns, higher frequency of extreme weather events, and a reduction of available water. These events indirectly increasingly harm agricultural producitvity (Brown et al, 2015), and can affect up and downstream transport, respectively causing less yield and more waste.

At the same time climate change also directly destroyes vast tracts of farmland: flash floods, hurricanes, storms, and drought deplete arable land. In 2011, the United States lost $110 billion worth of grain crops as a result of climate change-induced events. Weather-related disasters will become more frequent; it is the immediate result of man-made global warming. Consequently, vast swaths of farmland will be rendered unusable for farming (Mir et al, 2022).

efficiency and economy

The first two food threats showed that more crops must be grown as farmland is shrinking, or, more crops must be grown on less farmland. Thus, every square meter of farmland must be used more efficient. However, between 1960-2007, the sector's annual growth of yield per square meter fell from 3.2% to 1.5%. If this continues, the required yearly growth rate of 1.3% to feed 9.7 billion by 2050 cannot be achieved. Thus, research and development (R&D) must reverse the declining crop yield growth trend. This need for greater efficiency is especially acute in low-income developing countries, where 80% of the additional food supply must come from increased yields, while only 20% can be achieved by expanding farmland (Food and Agriculture Organisation, 2018). However, because agricultural R&D is dominated by the public sector in developing countries, innovation has been neglected.

International rates of return of 30-75% for agricultural R&D programmes should interest the private sector to boost the yield per square meter of farmland, but this comes with the condition that the poor must be able to use developments, otherwise efficiency won't increase on a large scale (Food and Agriculture Organisation, 2018). To beat hunger in developing countries, national economic growth will not automatically ensure success. Since 75% of the poor and hungry inhabitants of developing countries find residence in rural areas, their income is tied to agricultural results (directly or indirectly). Non-agricultural growth only benefits the rich, so it is key to establish agricultural advances to conquer hunger and malnutrition. Ways to approach this are food assistance, education, and training (Food and Agriculture Organisation, 2018).

cities as anti-ecosystems

In nature, ecosystems thrive on mutual needs. Animal waste feeds plants, plants feed animals, game feeds predators, and with the help of detritivores, decomposed animal carcasses return to the soil as a natural fertilizer for the next generation of plants. Plants excrete oxygen produced from absorbed carbon dioxide, while mammals take up and excrete these gases in reverse. All living things are interdependent, every ecosystem on Earth is a balanced closed loop. In years of scarcity, the cycle is reduced to feed those who can survive, and in rich years the inhabitants of ecosystems thrive and procreate. Ecosystems are still trying to work this way, but man's influence on their fragile equilibrium has done great damage. Why? Because humanity does not follow the natural rhythm of inflow and outflow.

Humanity's settlements have always grown, ignoring the decline in available natural resources. In stark contrast to the world around them, cities appear to have no growth limits. This doesn't just occur in prospering Western countries; it is also valid for the poorest. Countries as the USA and Abu Dhabi wildly exceed their yearly quota of natural resources considering the time it takes for those to restock. Over 50% of Earth's population found residence in urban areas, but those areas (ecosystems) do not provide enough resources to fulfil their demands. Almost all resources required for that are imported. The same goes for farms, which are basically adapted nature (deforestation).

If humanity keeps relying on harvesting resources from an environment it created itself (dependent on more and more fertilizers, herbicides, and pesticides) those artificial ecosystems will soon fail and leave mankind stranded. Society depletes farmland and (relatively) pristine ecosystems by stripping them of all resources, only for the flora and fauna that inhabit those systems to be displaced, harmed, or driven to extinction.

Another way modern agriculture disrupts ecosystems is runoff (and overuse) of chemicals into natural waterbodies. Through precipitation or overirrigation surpluses of fertilizer, herbicides, and pesticides run off to natural water bodies. Herbicides and pesticides disrupt the frail underwater ecosystem balance. Fertilizer exposes water to too many nutrients, causing rapid algae growth that block sunlight from under water flora, and later deplete water from oxygen upon algae dying (Despommier, 2010). Two examples of how overuse of chemicals can turn vibrant underwater flora and fauna into dead bodies of water (breaking down whole local industries and economies), follow now. First, a flood in 1993 along the midstream of the Mississippi River left ocean life in the Gulf of Mexico teetering for years to come. Mobilization of nitrates left in the soil after years of farming along the fertile banks of that river system created a dead zone that shut down all fishing (oysters, shrimp, fish) from Port Arthur, Louisiana, to Brownsville, Texas. Hurricane Katrina most likely caused the once productive coastal fishery to remain a dead zone for decades to come. Second, agricultural runoff from farms in Jamaica has reduced the coral reefs in the surrounding ocean to almost barren remnants of once-rich undersea life. This has shut down the local fishery industry (Despommier, 2010).

agricultural waste

In food production many resources are wasted throughout the process, including edible produce. This is a problem in regards to food security, because if this waste can be prevented the amount of additional food that needs to be produced can decrease. To get an overview of the severity of the problem, some **annual** key figures are listed and consequences are addressed (Food and Agriculture Organization, 2013):

1. Annually, 1.6 billion tons of primary product are wasted, of which 1.3 billion tons is edible;
2. Annually, 3.3 billion tons of kilogram $CO_{2\text{-eq}}$ greenhouse gasses are released as a result of food waste;
3. Annually, 250 km^3 of water used to produce food is lost or wasted (three times the lake of Geneva);
4. Annually, 1.4 billion hectares of land (28% of all farmland) produces food that ends up wasted;
5. Annually, direct economic food waste (excluding seafood) accounts for $750 billion dollar.

As the first food threat (*polulation and urbanization*) pointed out, at least 60% more food is needed to feed 2050's population. The realization that even without food waste there is not enough food to feed 9.7 billion (key figure 4: the 28% that can be saved is not even half of the targeted 60%) is shocking. This highlights that an improved, more efficient way of producing food is needed.

Naturally, 1.3 billion tons of food waste causes significant damage. Economically, annually $1 trillion dollars' worth of food is wasted (Food and Agriculture Organization, 2014). The environmental costs tally up to $700 billion dollars composed of the natural resources required to produce uneaten food, and the social cost amounts to $900 billion dollars; because if the global waste was reduced by 25%, 821 million undernourished people could be fed (Food Sustainability Index, 2018). So, reducing food waste is beneficial in three ways. First, farms, retail, and households can save money (Principato et al., 2021). Second, less water, land, and energy would be squandered to produce wasted yields (Food and Agriculture Organization, 2019).

Third, the negative effects of dealing with food waste on climate change can be avoided; the reason for public and private institutions to show a growing interest in the food waste phenomenon (Champions, 2018).

The United Nations takes food waste reduction very seriously; not for nothing is it part of Sustainable Development Goal (SDG) 12 (12.3.1: *responsible consumption and production*) among the 17 SDGs of the 2030 Agenda for Sustainable Development (United Nations, 2022b). Its aim: *"By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses"*. Food losses and food waste are considered in separate subgoals.

The environmental effect of agricultural food production and consumption reaches further than just on-farm activities. Significant losses of natural resources occur in food waste handling, refrigeration of food ultimately wasted (during transport, in stores, and in households), and as a direct result of food miles. Food miles represent the distance food travels from producer to consumer; the average dinner has 1,500 to 2,500 food miles (Astee & Kishnani, 2010). The food miles system has long been in question. Back in 2005, the CO_2 emissions for a pineapple grown in Ghana and sold in the United Kingdom were investigated. By plane, the total $CO_{2\text{-eq}}$ emissions come out to five kilograms per pineapple. Transported by boat, those would be ten times smaller (50 grams) (Smith et al., 2005). Thus, the absolute distance is misleading, the key to reducing the amount of emissions associated with each crop and inhibiting global warming and climate change lies in the organization of the food production industry.

A final problem regarding food waste is that very little of all food waste is composted and most ends up in landfills. If households were to compost their own waste, they could divert up to 150 kilograms from local collection authorities. That would reduce methane emissions released in landfills, one of the largest sources of greenhouse gases in the food waste sector (98% methane and carbon dioxide, produced when bacteria break down organic waste) (Food and Agriculture Organization, 2022).

human health

Thanks to the regulations of health organizations, no legal herbicide, pesticide, or fertilizer is harmful to human health (provided that the crops containing them are consumed in regular servings). However, in case of allergy or hypersensitivity to elements found in agricultural supplements (organophosphates, carbamates, etc.), consuming them may affect the nervous system. Others can irritate the skin and eyes. Some pesticides may be carcinogenic (a substance capable of causing cancer in living tissue). Thus, in general, agricultural supplements are not harmful to human health, but as long as agricultural systems require the usage of herbicides, pesticides and fertilizers, non-organic foods remain a danger to people with allergies and hypersensitivities to the aforementioned substances. The ideal agricultural practice would not need the added protection and nutritional value that agricultural supplements provide, but thrive entirely on the closed ecosystem balance (United States Environmental Protection Agency, 2022). As food threat 2 (*decrease in farmland*) indicates, ever more fertilizer is required to keep depleting farmland fertile; putting progressively more pollutants into food risking that their concentrations will, at some point, actually become dangerous.

agricultural stereotype

Farming used to be romanticized; living a simple life connected to nature. Farmers were people with good values and common sense, honest workers. Despite this, farming is traditionally an object of mockery.

As great as the difference between cities and farms was in relation to nature, as great was the difference in sophistication. Farming was seen as a profession for less intelligent people; smarter children used to move from farms to cities, to make a future for themselves and bring prosperity to the family they left behind. Conversely, IQ-wise less fortunate children were sent from cities to farms, because working in the fields was considered the only productive thing they would be good at. Later, shortly after their founding, English colonies in North America were a destination for African slaves. To this day farming is associated with slavery in America, so to leave their (family's) past behind, many African-Americans moved to the cities. The industrial revolution gave them and other people of colour a chance to realize middle-class stability and aspirations. Moving away from farms was seen as progress, leaving behind an undesirable past for a promising future (Despommier, 2010).

These stereotypes have persisted over the years, and to this day agriculture is an unattractive industry for many. This increases the pressure on today's farmers to provide the world with the food it demands while the workforce shrinks. The age of technology in which humanity now finds itself urges that innovative technology career paths are better than careers in agriculture. Despite behind-the-scenes innovation, agriculture continues to have a simple old-fashioned character in the youth's eyes. To secure sufficient food supply and attract high-tech interested young professionals to agricultural careers, the prospect of advanced farming systems within city limits is enticing. Such a development would kill three birds with one stone: first, relieve pressure on traditional farmers, second, interest the new generation in a career in agriculture, and third, gradually eliminate persistent stereotypes about farmers and their profession by displacing the sectors stale nature with innovative solutions (Despommier, 2010).

The research conducted in this chapter has been incorporated in the design of a hybrid urban vertical farm. Now, at its conclusion, references are made to the chapters in which the features identified as important in this chapter have been incorporated into the design.

- This thesis explores a way to grow more crops on a small footprint by hybrid urban vertical farming (huvf), addressing food threat 2 (decrease in farmland) and 3 (efficiency and economy);
- Recommendations are made on how a huvf can exchange resources with the urban environment to avoid importation, addressing food threat 4 (cities as anti-ecosystems) (p7 integration, c2 resources);
- The huvf growing system is designed to reuse non-uptake resources (p4 system, c2 design), thereby reducing resource wastage during cultivation, addressing food threat 5 (agriculutral waste);
- A huvf configuration can be built in the urban environment, nearby consumers, reducing food spillage during transportation, addressing food threat 5 (agricultural waste) (p7 integration, c3 urban);
- The huvf growing system works without herbicides, pesticides, and fertilizers (p4 system, c2 design) and thus avoids the risk of allergies and hypersensitivities, addressing food threat 6 (human health);
- A huvf unites advanced vertical farming and high-tech greenhouse construction, thereby avoiding an old-fashioned character, and can interest techies, thus addressing food threat 7 (agricultural stereotype).

in this chapter

Today, most crops are grown in one of three farming practices: open-field cultivation, greenhouse agriculture, or vertical farming. Each has its own (dis)advantages, and none combines all advantages. The three practices are discussed first, and then their strenghts, weaknesses, oppurtunities, and threats are bullet-pointed, and their carbon footprint is studied. At last, a proposal is made for an innovative agricultural practice that combines all the advantages and omits most of the weaknesses: hybrid urban vertical farming.

Ask a child to draw how crops are grown, and it will draw a crop rooted in soil, irrigated by rainfall, and lit by sunlight. Ask a European professional grower to do the same, and he will draw the same crop rooted in rock wool, irrigated by a drip system, and lit by (supplemental) artificial light. The child draws open-field cultivation, the grower draws greenhouse agriculture. Now ask an agricultural expert the same, and he will fill a sketchbook with farming practices, because ever since humanity started working the land to cultivate crops on it, varieties have been developed to optimize yields. Today, however, most crops are grown in one of three ways: open-field cultivation (85%), greenhouse agriculture (13%) and vertical farming (2%).

open-field cultivation

With an 85% market share globally, open-field cultivation is the most widely used crop-growing technique. In this technique, crops are grown in soil, in open air, using fertilizer, pesticides, and herbicides. Open-field crops are rain-fed, supplemented by manual irrigation (Barbosa et al, 2015). Besides farmland this practice requires machinery (tractors) and buildings to store machinery, resources, and harvests in. Preferably, the farmland is as big as possible to achieve economies of scale and make a profit. Dutch open-field farms are 15 hectares in size (CBS, 2021), while American ones can be as large as 180 hectares (United States Department of Agriculture, 2022). Depending on the crop, multiple growing cycles are possible; in the Netherlands, lettuce growers can harvest up to three times a year. To prepare land for open-field cultivation it must be leveled and stripped of vegetation; especially in forested regions this causes large-scale deforestation and reduces the natural capacity of carbon sequestration. Also, during the use of an open-field farm, the environment is polluted because any resource (water, fertilizer, etc.) that is not uptaken by crops runs off into nature, which can lead to eutrophication of surrounding ecosystems. Because an open-field farm is not bordered by an enclosing structure, unused resources cannot be captured and reused; thus, some resources that enter the farm are essentially wasted. Thus, even though open-field cultivation requires little equipment, its land preparation and non-circular use of resources make it unsustainable.

greenhouse agriculture

Growers want control over the climate in which crops grow. In temperate climates, the fluctuations in conditions associated with open-field cultivation are acceptable, but in more unfavorable climates, an artificial climate must be created, and that can be done in a greenhouse. Greenhouses come in many varieties; from polytunnels that protect crops from wind and rain only, to high-tech greenhouses in which the CO_2 concentration, temperature, humidity and light intensity can be changed real time. In all cases, the glass envelope allows sunlight to be used as a passive lighting and heating source, supplemented by artificial lighting on cloudy days and mechanical heating in cold times (Graamans et al., 2018). This thesis distinghuishes between two types of greenhouses: s*oil-based* and *non soil-based greenhouse agriculture*. In the first technique, crops root in soil in which non uptaken water and nutrients drains away so it cannot be reused. In the second technique, crops root in soilless substrates in which non uptaken resources can be captured and reused.

Within non soil-based greenhouse agriculture, there are three main methods: *hydroponics*, *aeroponics*, and *aquaponics*. Each is introduced, as well as their advantages and disadvantages.

hydroponics

Hydroponics is the most widely used soilless cultivation method in horticulture. It is the process of growing plants, without soil, by exposing their roots regularly to water-based mineral nutrient solutions in aqueous solvents. Plants' roots are often supported by an inert medium as perlite, gravel, or other substrates. The Greek words *hydro* (water) and *ponos* (labour) are the literal translation of the operation of this non soil-based system; plant nourishment is borne by water only (Mir et al., 2022). Three common hydroponic systems are: 1) a wick system in which a wick capillary draws a nutrient solution from a tank into the medium in which crops are rooted, 2) a drip system in which a nutrient solution is dripped onto crops' media through a drip line, and 3) the nutrient film technique, or NFT, in which a thin 2-3 mm layer of nutrient-enriched water is intermittently poured along suspended roots.

aeroponics

Aeroponics is an improvement of the hydroponic method; only the roots of crops are misted with a nutrient-rich solution. Because the solution is atomized directly on the roots, which are suspended in the air, aeroponics does not require soil or even an inert medium. The use of atomization reduces water requirements per crop by more than 70% compared to hydroponics (Mir et al., 2018). The word aeroponic is derived from the Greek words *aer* (air) and *ponos* (labor), which defines its deviation from hydroponics because here air carries nutrition instead of water. This has several advantages: 1) roots being exposed to oxygen has been proven to be beneficial for root development (Soffer et al., 1991), 2) crops grown in an aeroponic system have maximum access to CO_2 which boosts photosynthesis and makes crops grow faster in aeroponics than in hydroponics, and 3) soil- and water-borne diseases are avoided.

aquaponics

The aquaponic method combines hydroponics and aquaculture, creating a symbiotic relationship between plants and fish (Mir et al., 2022). It offers resource efficiency by using fish waste as a natural fertilizer and reducing water usage by recycling water within the system. Additionally, it provides a diversified output by enabling the production of both plants and fish. However, maintaining the delicate balance of the system can be challenging, and initial setup costs for equipment such as fish tanks and filtration systems can be higher compared to conventional farming. Despite these considerations, aquaponics presents a sustainable and integrated approach to farming, particularly in areas with limited resources and arable land. However, because aquaponics uses ten times more water than soil-based agricutlure, it is unsuitable for regions with water scarcity (Diver, 2006).

vertical farming

The newest method of crop production is vertical farming; the vertical stacking of growing beds. This type of farm is built in enclosed structures that are artificially heated and lit so that growers have control over the climate, known as controlled-environment agriculture (CEA) (Jensen, 2002). For disease control, vertical farms generally do not use soil-based methods but hydroponics, aeroponics, or aquaponics. Vertical farms can grow crops in the urban environment because of their common locations in vacant buildings, warehouses, shipping containers and barn, unlike conventional farming practices (Birkby, 2016).

The modern vertical farm was conceived by Dickson Desprommier, a professor of Public and Environmental Health at Columbia University, in 1999. He designed a skyscraper that could feed 50,000 people; a yield that no conventional agricultural practice on the same footprint can come close to. No such design has yet been built (yet), but the state-of-the-art technologies he proposed have been incorporated into existing applications, yielding ten times that of conventional farming principles (Cooper, 2017).

Vertical farming has four main advantages: 1) an increased crop yield per footprint reduces the demand for farmland, 2) soilless cultivation on different layers makes it possible to cultivate different crops per farm 3) climate conditions are completely unaffected by weather influences like clouds or overly intense sunlight, unlike open-field cultivation and greenhouse agriculutre, and 4) reduced demand for farmland leaves nature undisturbed for plants and animals, further preserving local flora and fauna (Navarro & Pereira, 2012). Of course, these advantages are enticing to companies, hence vertical farms raised unprecedented amounts of financing in North America and the Middle East. Venture capitalists, governments, financial institutions, and private investors are among the leading investors in the sector.

Naturally, vertical farming comes with disadvantages as well. First, vertical farming technologies face economic challenges with high start-up costs. In Victoria, Australia, a ten-story vertical farm is calculated to cost 850 times more per square meter of farmland than a conventional farm (Benke & Tomkins, 2017). Second, the energy demand of artificial light poses another costly challenge. If non-renewable energy were used to fulfil it, vertical farms would produce more pollution than conventional cultivation practices. Omdat zonlicht zich niet evenredig over teeltlagen kan verdelen, en zeker (wanneer verdeeld over meerdere lagen) niet intens genoeg is om te voorzien in de lichtbehoefte van ieder plantje, moet een vertical farm wel kunstlicht gebruiken. Heating and cooling, the most significant energy demands after lighting, consume a substantial portion of the energy, as seen in a lettuce production case study. For every square meter of cultivation area, 5.4 m2 of solar panels are needed to (sustainably) meet energy needs. It is not difficult to understand that a vertical farm does not have that many square meters of wall and roof surface; thus, the footprint of a vertical farm becomes larger purely because solar panels must be placed elsewhere. These limitations underscore the energy-intensive nature and cost challenges of vertical farming, urging the need for solutions to make it more feasible and sustainable. Besides the energy challenge, there are also environmental challenges in terms of removing carbon emissions for heating/cooling, preventing (artificial) light pollution to the environment, removing ventilation air without leaking CO_2, and discharging liquid water without eutrophying the environment. Summarizing, vertical farms are not sustainable, even though their fully-controlled nature and high yields makes them appear to be; energy use prevents this farming system from being a sustainable food source *right now*.

swot analysis

The next page presents a SWOT analysis for open-field cultivation (abbreviated as OF), the two variants of greenhouse agriculture; *soil-based* (GHs) and *non soil-based* (GHh), and vertical farming (VF). In it, strenghts (S), weaknesses (W), oppurtunities (O), and threats (T) of each are given. Naturally, there is overlap between the farming practices, but the analysis was conducted with the intention of discovering where there is no overlap yet, particularly of the strenghts and oppurtunities. Later in this section the swot analysis, among other things, is used to propose an innovative farming practice that combines strenghts and oppurtunities, and excludes weaknesses and threats as much as possible.

Based on the SWOT analysis in *figure 1* conclusions are bullet listed. From OF, through GHs and GHh, to VF, it stands out that the more technologically advanced systems have an...

- ... increasingly higher yield per square meter farmland;
- ... increasingly lower need for fertilizers, herbicides, and pesticides;
- ... increasingly higher likelyhood to have low food miles;
- ... increasingly higher influence on cultivation climate;
- ... increasingly higher certainty of crop yield and quality;
- ... increasingly higher possibility of long cultivation periods;
- ... increasingly higher energy demand to operature the farming practice;
- ... increasingly higher start-up cost due to more technologically advanced nature;
- ... increasingly higher degree of resource circulation and outwash prevention;
- ... increasingly lower utilization of ecological factors (sunlight, rainwater).

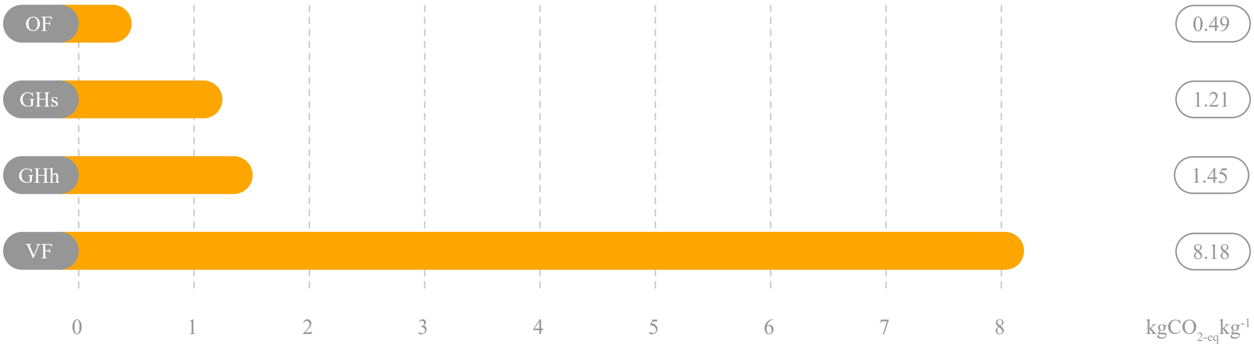
	S	W	O	T
OF	economies of scale use of sunlight and air farmland availability	no climate control pesticides required soil depletion (plough)	demand for organic crops genetically modified crops soil regeneration	climate change/weather reduced demand farmland shrinkage
GHs	year-round production basic climate control control of resources	high initial investment requires maintenance limited crop diveristy	demand for local crops automation and AI renewable energy	farmland availability competition of GHh and VF changing regulations
GHh	year-round production basic climate control reuse of resources	high initial investment power outages limited crop diveristy	demand for local crops automation and AI renewable energy	farmland availability competition of VF changing regulations
VF	year-round production perfect climate control reuse of resources	high initial investment high energy demand high-tech nature	demand for local crops automation and AI stacking extra layers	plot/building availability rising energy prices changing regulations

figure 1: swot analysis of farming practices (own, 2023)

carbon footprint

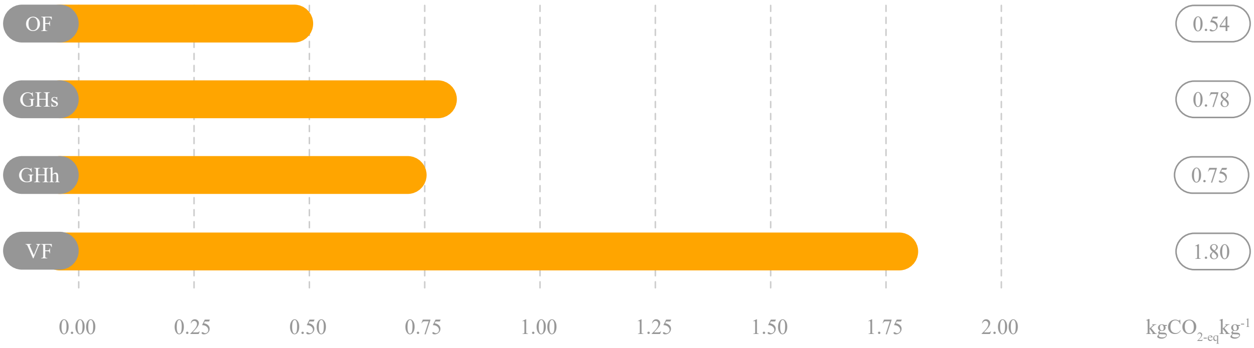
Just because vertical farming can reuse resources better than open-field cultivation does not mean that the former is more sustainable, and conversely, the use of sunlight does not necessarily make open-field cultivation more sustainable than artificially lit-using vertical farming. To know how sustainable each farming practice is one should look at the carbon footprint per unit of crop of the production process, including up- and downstream flows. That is what Blom et al (2022) did. A study of the carbon footprint of various lettuce farming practices was conducted and it proved that vertical farming is the least sustainable in both a baseline and an alternative scenario. Important to note: the data used in the calculations of Blom et al was received from recognized databases for horticulture in the Netherlands and are therefore valid.

The data for the vertical farm, is case-specific and may vary between vertical farms. *Graph 1* presents the results of the baseline calculation, in which no alternative (favorable) scenarios have yet been included. The carbon footprint is expressed in kilograms CO_2-equivalent per kilogram of fresh weight crop produce, meaning that emissions have been converted to the CO_2-equivalent to allow for an easy comparison between farming practices.



graph 1: baseline carbon footprint analysis of farming practices (adapted from Blom et al, 2022)

Environmentally, vertical farming (VF) performs worst: with 8.18 $kgCO_2$-eq kg^{-1} it is 16.7 times more polluting than open-field cultivation, and respectively 6.8 and 5.6 times more polluting than soil-based (GHs) and non soil-based (GHh) greenhouse agriculture. Compared to the other farming practices the high carbon footprint of vertical farming is mainly due to emissions in the crop upstream stage (producing seedlings), the crop core stage (electricity, water, and nutrients), and the crop end-of-life stage (packaging materials).



graph 2: alternative carbon footprint analysis of farming practices (adapted from Blom et al, 2022)

The baseline scenario is straightforward, for the alternative scenario three assumptions are introduced: 1) the carbon sequestration capacity decreases when changing land to farmland (significant for open-field cultivation) 2) farming practices use polypropylene packaging (reduces the crop upstream stage by 45%), and 3) energy is supplied by renewable energy/biofuels (reduces the crop core stage by 83%). *Graph 2* presents the carbon footprint of the alternative scenario. Noteworthy, for vertical farming electricity use still is **66% of the total carbon footprint**. Even though the new packaging reduces end-of-life emissions by 56%, VF still is the most unsustainable. The carbon footprints of GHs, GHh and VF are reduced by 35%, 48% and 78%, respectively. Caused by the loss of carbon sequestration potential, the OF's carbon footprint increased by 11%. The factorial difference between VF and OF is reduced from 16.7 to 3.3 times worse.

The carbon footprint analysis shows that, even in the alternative scenario, vertical farming *as it is now* is not a competitor to other farming systems based on its sustainability. To make vertical farming a true competitor to the conventional farming practices, the greatest gain can be made by lowering its electricity use. Furthermore, better (re)use of propogation and packaging materials (crop upstream and downstream stage), better (re)use of resources (crop core stage), and building vertical farms in buildings with a low embodied energy (farm upstream stage) can help reduce the total carbon footprint significantly.

venn diagram

Based on the SWOT analysis performed earlier, a series of VENN diagrams are created. In it, two agricultural practices (OR, GHs, GHh, and VF) are placed in adjacent circles, and the overlap between the circles characterizes a shared favorable feature. This sequence, shown in *figure 2*, shows that no favorable feature is shared by all four agricultural practices; there is always at least one that does not have it. The last VENN diagram is particularly important, in which the favorable feature ‘*stacked; high yield per* m^2’ is linked to vertical farming (VF). No other farming practice shares this feature, however, in this day and age when a more efficient use of farmland is essential for humanity to be fed by 2050, it is of utmost importance that new farming practices do incorporate that stacked feature. That conclusion, and others that can be drawn from the series of diagrams, are important in identifying the sector’s gap.

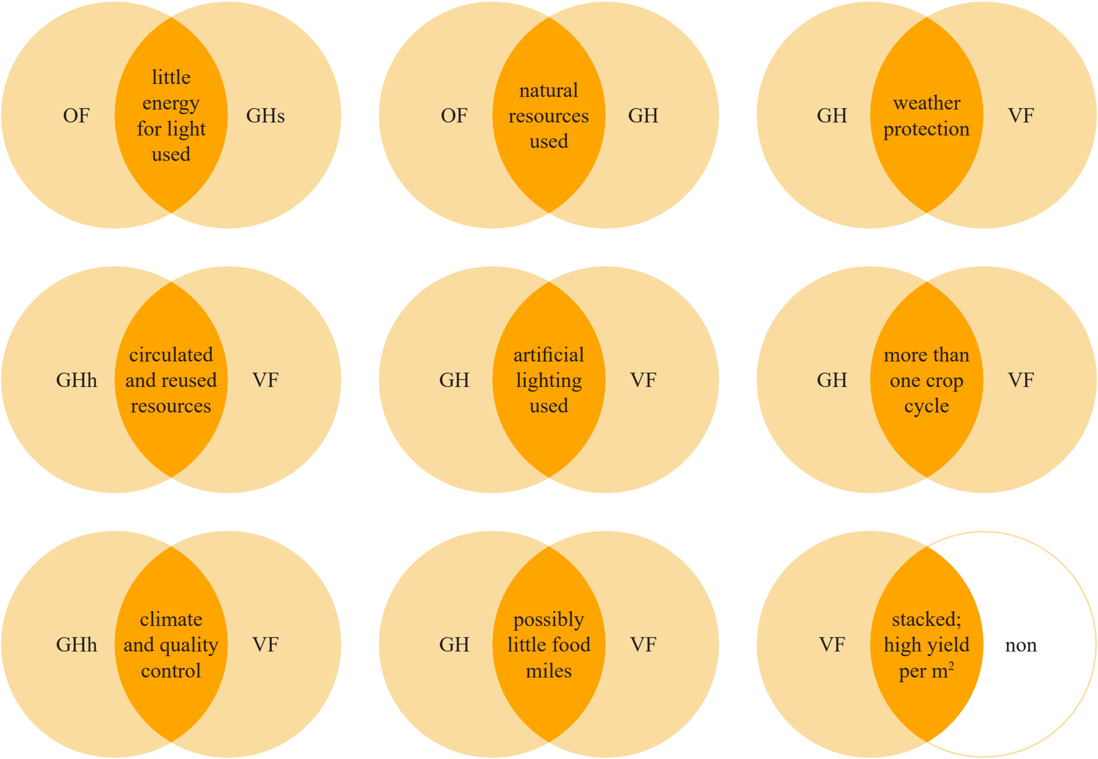


figure 2: venn diagrams of farming practices (own, 2023)

sector’s gap

By combining the results of the analysis methods, the sector’s gap can be revealed. Features that resulted from the comparisons are numbered, and are later addressed in the description of the sector’ s gap again.

The SWOT analysis revealed that there is no farming practice that allows both high yields (1) *and* climate/quality control (2) for a low initial investment. The carbon footprint analysis showed that vertical farming is not yet a sustainable solution because it uses too much electricity for artificial lighting (3), and the crop upstream and downstream stages cause too many emissions (4). Finally, the VENN diagrams illustrated that there is not yet a farming practice that uses both sunlight *and* stacked cultivation, to minimize energy cost (5) *and* increase yield per square meter of farmland (6), whilst being protected from the weather (7) and (re)using resources (8), that can be built in the urban environment (9). Concluding from these nine features that summarize the results of the comparison of farming practices, the sector's gap is identified as follows:

A farming practice that reuses resources (8) by using a non soil-based greenhouse agriculture method that allow precise control of nutrition and quality (2a). The farm should be a hybrid between greenhouse agriculture constructions and vertical farming stacked systems to provide full control of the growing conditions (2b), allow the use of daylight through a glass deck/decrease the use of artificial light (3, 5), and being very efficient with the square meters of farmland to achieve high yields (2, 6). A closed structure will provide crops from (worsening) weather conditions (7). At last, being able to grow many crops on a small footprint allows these type of farms to be situated in the urban environment (9), which means that the up- and downstream emissions of transport and long-haul packaging can be reduced (4).

solution proposal

Based on the identified gap in the sector, a solution is proposed to combine the favorable features of conventional farming practices and omit the features that cause the carbon footprint of vertical farming to be so high. The proposal: a modular small-scale rebuild greenhouse in which a vertical farm typology is built that works hydroponically. Rebuilding the construction reduces the carbon footprint of the structure, allowing daylighting reduces the carbon footprint of artificial lighting, and stacking cultivation allows for high yields on a small footprint. The modular nature of the farm links to the circular approach of traditional greenhouse construction (p3 module c1 principles). Finally, the small scale allows a farm to be built in (proximity to) the urban environment, have short/no ransportation, and integrate with the city's social amenities (education, labor, markets, etc.). How this solution proposal was incorporated into a full-fledged thesis research, and what the research questions, method, and structure are follows in the next chapter (p1 intro c3 research).

The research conducted in this chapter has been incorporated in the design of a hybrid urban vertical farm. Now, at its conclusion, references are made to the chapters in which the features identified as important in this chapter have been incorporated into the design.

- Huvf modules and growing systems are build with reused greenhouse componentry which reduce the carbon footprint of the construction (farm upstream stage) (p3 module c2 design, p4 system, c2 design);
- By optimizing the rotation (in or out of sync) and spacing of huvf growing systems artificial lighting is reduced by 34% (could be by 56% if space was no issue) (crop core stage) (p4 system c3 light);
- The huvf growing system irrigates the crops using a nutrient film technique (NFT) that facilitates easy uptake of water and nutrients and drainage and reuse of non uptaken resources (p4 system c2 design);
- A rebuild hybrid urban vertical farm configuration made of a 2.9 hectares greenhouse has a footprint of 1,296 m^2 (72 by 18 meters), and thus fits in the urban environment (p7 integration c3 urban).

research

in this chapter

After describing the threat of losing food security in 2050 and identifying the gap in the horticultural sector/ proposal of an innovative farming practice, research can be drawn up. In this chapter, the relevance is briefly recalled for this purpose, a main research question is established followed by a series of sub-research questions including objectives and approach. Then the hypothesis, method and structure are discussed. Finally, the company where the author gathered a lot of information, VB, is introduced.

relevance

Today's farming practices are not efficient enough to feed 10 billion people by 2050. Therefore, a new farming practice must be developed. Thus, this thesis contributes to the prevention of a global disaster (*social relevance*). Should the research not have a saturating result it will have helped the scientific community and its accumulated knowledge to ultimately arrive at a viable sustainable farming system alternative (*scientific relevance*). The envisioned growing system has three features, first, *reusing* existing material, lowering the carbon footprint, second, *reducing* the need for artificial lighting by using daylight, lowering energy consumption, and third, *recycling* of waste streams, increasing circularity and lowering the need for produced resources. These are the three pillars of the *trias energetica*, the fundamental principle of sustainable development. The fact that this thesis embodies those pillars proves its relevance to contemporary ideas.

Since the author is doing a graduate studio within the Delft University of Technology MSc Building Technology, at the Faculty of Architecture, the research should be relevant to the degree as well. A hybrid urban vertical farm (graduation research) aims to increase the horticultural sector's circularity by *reuse of existing structures* (graduation studio). This requires technical knowledge about components, properties, and reuse possibilities. This makes it relevant to the MSc track Building Technology. As the research also touches on reuse of waste streams and embedding in the urban environment, it is relevant to the broader master direction, MSc Architecture, Urbanism, and Building Sciences (AUBS) as well.

main research question

In order for research to result in the design of an innovative farming practice that can fill the identified gap in the horticultural sector, the main research question is formulated as following: "*How can a modular hybrid urban vertical farming practice be constructed with reused greenhouse components, and become high yielding, sustainable, and economically feasible?"*

sub research questions, objectives, and methods

Each characteristic in the main research question is covered in a sub research question. The answer to each is answered in the various parts, and together they answer the main research question. These questions are:

1. Regarding the aspect ".... reused greenhouse components": *"What are common greenhouse components and how can these be refurbished in order to be reusable?"*. It is answered in p2 reuse by means of an overview of common greenhouse components and an approach to refurbish them;

2. Regarding the aspect ".... reused greenhouse components": *"What components become available when a greenhouse is demolished?"*. It is answered in p3 module by means of an overview of a case study greenhouse's components that can be reclaimed upon demolition;

3. Regarding the aspect “urban modular farming”: *“How can modules be built from reused greenhouse components and what conditions should modules meet?”*. It is answered in p3 module by means of an illustrated overview of the principles of greenhouse construction to which structures must conform **and** an overview of the different modules to design based on those greenhouse construction principles **and** a design for each of the different modules in 3D;

4. Regarding the aspect “become high yielding”: *“What are strong characteristics of existing vertical farm typologies and how can they be combined?”*. It is answered in p4 system by means of an analysis of vertical farm typologies, their floor space index, and desirable features **and** a design for a growing system that reuses a case study greenhouse’s components;

5. Regarding the aspect “sustainable, and economically feasible”: “*How can as much daylight be utilized to minimize energy costs for artificial lighting?*”. It is answered in p5 optimize by means of an optimization of the orientation of systems to receive maximum daylight **and** an optimization of the spacing between systems to receive maximum daylight;

6. Regarding the aspect “become high yielding”: *“How can a growing system use an available footprint efficiently?”*. This is answered in p5 optimize by means of an optimization of growing system placement in modules to obtain the highest floor space index (FSI) **and** an optimization of a module configuration to get the highest possible reuse percentage of a case study greenhouse’s components;

7. Regarding the aspect “sustainable, and economically feasible”: “*How much emissions are saved when building a farming system with reused components?”*. It is answered in p6 carbon by means of a carbon footprint calculation of the construction of the optimal hybrid urban vertical farm and its growing systems **and** a carbon footprint calculation of the construction of a case study greenhouse **and** a comparison of the carbon footprint per crop of a hybrid urban vertical farm and a greenhouse;

8. Regarding the aspect “urban modular farming,”: *“How can urban farms connect to and utilize urban infrastructure and facilities?”*. It is answered in p7 integration by means of an overview of ways to substitute finite resources by renewable resources **and** an overview of ways to integrate a (hybrid urban) vertical farm with the socio-economic facilities that an urban infrastructure has to offer;

9. Regarding the aspect “sustainable, and economically feasible”: *“How can greenhouses be designed more modular to better enable future reuse?”*. It is answered in p7 integration by means of a reflection on on the circularity of individual greenhouses, and greenhouse construction as a whole.

hypothesis

It is estimated that it is possible to design a high yielding, circular and sustainable, economically feasible, hybrid urban vertical farm (huvf) by reusing reclaimed greenhouse components. After writing p1 intro, and understanding strengths and weaknesses of conventional farming practices, a huvf can be designed by rethinking ingrained anti-circularity perceptions within the industry, and repurposing components that are thought of as waste. At the start of this research it is deemed a questionable goal to not have a significant lower yield with the proposed hybrid urban vertical farm compared to closed box system vertical farms.

The 100% controllability and perfect conditions the latter offers will not be achievable in a greenhouse-like construction that deals with various weather conditions, and thus varying amounts of sunlight, daylight, temperature, and humidity. All of these are variable conditions that decrease the controbility of the culitivation climate.

However, it is not the goal to achieve the same yield in a hybrid urban vertical farm, as the goal of artificial lighting in it is to supplement crops with the light they do not receive by daylight only. This is opposite to a vertical farm where crops are given an overdose of artificial light in order to undergo as much photosynthesis and grow as fast as possible. So in terms of growth cycles and yield, a hybrid urban vertical farm is estimated to be inferior to a vertical farm. However, since a hybrid urban vertical farm will feature a layered growing system in which crops get the same amount of water, nutrients, and light (supplemented artificially) as they do in open field cultivation and greenhouse agriculture, it will be superior to those conventional farming practices in regards to yield per square meter farmland.

At the commencement of the research, after initial practical input, there is much scepticism as to whether daylight can possibly provide enough light intensity in a layered farming system. There is a reason why crops in controlled-environment agriculture (CEA) are artificially illuminated at each layer. The hypothesis whether this problem can be solved is: it can be partially solved. In summer, when sunlight is the most intense and available, the crops can get enough light by rotating them towards the greenhouse deck in intervals, in other seasons artificial light will have to supplement crops with all the light they need. Nevertheless, awareness of this lighting challenge will benefit this research, as the scepticism will be addressed in this thesis to minimize the need for artificial light.

methodology

Naturally, a broad knowledge base on crop needs and reuse of greenhouse materials is laid before design by means of scientific literature review, which is further deepened during the design process. However, to design a viable hybrid urban vertical farming module, the literature based research in this thesis must be tested against real-world conditions at every step. Therefore, a collaboration is established with VB (greenhouse design and construction management in Naaldwijk, the Netherlands). This collaboration provides access to a broad network of specialized horticultural companies in the Atrium Agri consortium, of which VB is a member, across the entire breadth of greenhouse construction. VB and Atrium Agri provide the practical input necessary to design structurally sound huvf modules.

However, since VB mainly works with new materials, this consortium lacks the knowledge needed to design a feasible and practicable reuse methodology. Therefore, practical knowledge to support the literature review on component reuse is sought from greenhouse demolition companies. Besides, to address the (dis) advantages of a hybrid farming system, manufacturers of growing systems both within and outside the Atrium consortium are contacted. The decision to consult multiple companies was made to circumvent company's preferences for their own systems. Information on urban integration is primarily found in papers.

Furthermore, the intention is obviously to make use of the knowledge and networks of the first and second mentors, Ir. A.C. Bergsma (Architectural Engineering & Technology) and Dr. A. J. Jenkins (Environmental & Climate Design), respectively.

The first four parts of this thesis (p1 intro, p2 reuse, p3 module, and p4 system) uses the design-by-research approach, because the design of modules and a growing system (*design*) is the result of gathered knowledge through literature and practice (*research*). The following two parts of this thesis (p5 optimize and p6 carbon), in which the design is optimized, use the research-by-design approach. In it, knowledge about which layout is the most efficient (*research*) is acquired by testing out various designs (*design*). The final *design* part, p7 integration, is again design-by-research, although the design is theoretical and advisory.

structure

After p1 intro, p2 reuse describes the components in greenhouses and researches how to reuse them. To this end, knowledge from literature and practice is combined in finding *micro-solutions* that ensure that disassembled parts can be reused as efficiently and sustainably as possible. In p3 module, a case study greenhouse is introduced, and its components are explored. Those form the toolbox of components for the design of nine modules in that section. The nine modules are designed in line with traditional greenhouse construction principles (the use of a building grid and set ways to transfer wind loads) that are discussed as well. In p4 system crop requirements are addressed first, and existing vertical farming technologies are analysed second. Then knowledge of both studies is combined in the design of an innovative hybrid vertical farming system that meets crop requirements and combines the strengths of existing typologies. After the design, a threefold optimization of artificial light is performed; first on whether or not the systems should rotate synchronously, then on spacing between systems and space efficiency.

In p5 optimize it is researched how growing systems should be placed in modules to achieve the highest floor space index (FSI), and what configuration of modules leads to the highest reuse percentage of the most common construction element, midfield columns. This part results in a certain module configuration with a certain number of growing systems in it. In p6 carbon, the carbon footprint of the optimized configuration including its growing systems is calculated. This is compared to the carbon footprint of the case study greenhouse from which the components originate. Combined with the data of how many crops can be grown per square meter in both the hybrid urban vertical farm and the case study greenhouse, the carbon footprint per crop can be determined. This comparison proves which of the two farming practices, innovative or conventional, is more sustainable. Finally, p7 integration shows how the optimized configuration can be embedded in the urban environment and gives recommendations on how significant finite resources could be substituted by renewable alternatives to make the design as a whole more sustainable. It ends with a reflection on the circularity of individual greenhouses, and greenhouse construction as a whole.

In p8 conclusion, the research questions (main and sub) of this thesis are answered. A discussion addresses the additional research that could/should be done to add to the completeness of the research. Furthermore, recommendations are expressed to test the design, as well as recommendations to improve it. At last, a reflection looks back on the entire process undertaken during the graduation period.

vb

Verbakel Bomkassen was founded in 1966 by brothers Joop and Aad Verbakel. Originally known as J & A Verbakel heating, the company started in De Lier, focusing on providing heating solutions for the Dutch greenhouse industry. They soon expanded their operations to Belgium, France, Germany, and eventually the USA in the 1970s, with their first heating project on Long Island.

As the business grew, the Verbakel brothers realized that solely supplying heating systems had limitations. In 1983, they acquired Bomkas Kassenbouw in Wateringen to broaden their activities. This move proved successful, and the Verbakel-Bomkas combination secured contracts in Saudi Arabia, China, and India. With the integration of greenhouses, climate control systems, and other horticultural systems, Verbakel-Bomkas transformed into a comprehensive provider of horticultural solutions. In 1992, they decided to outsource component production, allowing them to focus on expanding their services.

The company's expansion continued, and in 1996, they ventured into field heating installations outside of horticulture, constructing one for soccer club PSV in Eindhoven. This marked the beginning of their expansion beyond traditional horticultural applications. In 1997, Edward Verbakel, son of Aad Verbakel, joined the company, initially focusing on foreign markets and later joining the management in 2001. As the company grew, a new location was built in De Lier in 2005. Recognizing changing market dynamics, Verbakel-Bomkas decided to export more and explore opportunities in the utility and energy sectors . To reflect the company's broadened structure and activities, Verbakel-Bomkas changed its name to VB in 2012 (Soszna, 2020).. The company celebrated its 50th anniversary in 2016, during which Aad Verbakel was honored as a Knight of the Order of Orange Nassau. In 2018, VB purchased land for a new sustainable business building, which was completed in 2020.

The author of this thesis reached out to VB, seeking access to knowledge, project drawings, and specialized horticultural companies in the Atrium Agri consortium, whilst working on his own research question. VB provided the author with the desired opportunity for practice-tested research and design. Additionally, the author spent one or two days a week working on assignments from VB to gain hands-on knowledge.

figure 3: VB office in Naaldwijk (Groentennieuws, n.d.)

part two

reuse

p2 reuse

in this part

This part, p2 reuse, is composed of three chapters: first, because not every reader will have knowledge of the components that form a greenhouse, c1 components explains how a greenhouse is put together, and when relevant properties of materials are explained. Second, combining literature and practice, c2 refurbish examines how different materials and components can be reclaimed and refurbished. Knowing if certain components can be reused is important, because in p3 module a case study greenhouse will be dismantled whose reusable components form the toolbox of available material for the design of hybrid urban vertical farm modules. Third, to clarify that even though some elements are reusable even when they cannot be diassembled completely, c3 circularity shines a light on the circularity of an individual greenhouse. Fourth, c3 roadmap provides a guideline on the practical application of hybrid urban vertical farming.

To gain insight into practical approaches to (re)using horticultural steel, a visit was made to Duijnisveld Greenhouse Structures, Poeldijk, the Netherlands. This company processeses (cutting, drilling, and welding) steel profiles that are imported from southern Europe. The person spoken to is company director Robbin Duijnisveld. The visit is refered to as *(Duijnisveld, R. [Duijnisveld], personal communication, January 18, 2023)*.

To gain insight into practical approaches to (re)using horticultural aluminium, a visit was made to BOAL systems, 's-Gravenzande, the Netherlands. This company processeses (cutting, drilling, and welding) aluminium profiles. The person spoken to is after sales manager Koos van der Ende. The visit is refered to as *(van der Ende, K. [BOAL], personal communication, January 20, 2023)*.

To gain insight into practical approaches to (re)using greenhouse components, a visit was made to Handelsonderneming A.C. van der Knijff B.V, Hoek van Holland, the Netherlands. This company disassembles greenhouses and refurbishes and resells components. The person spoken to is company owner Arend van der Knijff. The visit is refered to as *(van der Knijff, A. [van der Knijff], personal communication, December 10, 2022)*.

c1 **components**
c2 **circularity**
c3 **refurbish**
c4 **roadmap**

in this chapter

Greenhouses seem to be simple constructions: a steel structure with a transparent aluminium/glass envelope that transfers loads to a foundation. And it actually is that simple, thanks to years of research and development in the steel and aluminium (extruding) industry. It is mainly the growing systems and climate control installations that enhance the high-tech character of modern (Western) greenhouses. In this chapter the steel, aluminium, and glass elements are discusses, as well as common climate control installations.

steel

The primary load-bearing structure of a greenhouse is made of steel: a strong assembly of columns, trellises and braces. Together these carry the deck, growing systems suspended from trellises and wind, rain and snow loads. Vertical forces are transmitted via trellises (which consist of a top and bottom girder connected by diagonals, on which gutters located *between* columns bear down) to the columns (on which gutters located *above* columns bear down). Horizontal forces are transferred to the foundation through wind bracing in the roof to either midfield-bracing (inside the greenhouse, between columns), or to the end or side walls. Although not made of steel, aluminium gutters can also transfer horizontal loads parallel to the greenhouse gutter direction (Dutch Greenhouses, n.d.-a). The secondary load-bearing structure carries the gables and the wind loads on it. The wind load on glass is transferred through aluminium rods to steel purlins, which in turn bear down on the columns of the primary load-bearing structure. Purlins are used to prevent the gable from having to span several meters between columns, but instead be continuously supported.

In greenhouse construction, the most commonly used steel variant is S235, where the S stands for structural and the digits indicate the yield strength in MPa. Thus, S235 starts to flow when a load over 235 N/mm^2 is applied. The ultimate strength of S235 is 360 MPa, up to that load it yields, after it breaks. Some other relevant S235 properties are the density of 7,850 kg/m^3, the unit weight of 78.5 kN/m^3, and the modulus of elasticity of 210,000 MPa (Eurocode Applied, n.d.) (Duijnisveld, R. [Duijnisveld], personal communication, January 18, 2023).

aluminium

Aluminium is used as connection between glass and steel; the largest aluminium component is the gutter, which collects rainwater and snow and provides strength (although minimal) in the gutter direction of the greenhouse. Greenhouse gutters also have a function on the inside of the greenhouse; there they trap condensation and prevent dripping on the crops below. Deck rods (which hold glass panes, polycarbonate panels or sandwich panels in place) are connected to gutters at the bottom and to a ridge at the top; together, these three elements form the characteristic triangular morphology of greenhouses. Because of the close connection between glass, rods, the gutter and the ridge, the deck system effectively acts as one large gutter.

Aluminium rods in the gable also hold the cladding; most rods (and gutters) are made to hold four millimeters thick material, the standard for horticultural glass, but they can be made to hold thicker material, such as polycarbonate panels (16 mm) or sandwich panels. Because the corners of a greenhouse are exposed to high wind loads, vertical rods in the gable are spaced closer there to reduce the wind loads to which each area between rods is exposed. For the same reason, gutters along sidewalls are stronger than midfield gutters (Dutch Greenhouses, n.d.-b). To prevent profiles from leaking and scratching glass, rubbers and PVC strips are inserted into them. Current systems are dry-coupled and completely dismantleable when demolished.

Aluminium is one of the lightest engineering metals, with a strength-to-weight ratio superior to that of steel. Its density is about one-third that of steel (2,755 kg/m^3), making it one of the lightest commercially available materials. Those properties make it suited for deck and gable systems, which themselves add little weight. Aluminium has a low tensile strength, but adding alloying elements as manganese, silicon, copper, and magnesium can increase aluminium's strength properties (Shen et al., 2022). As temperature decreases, aluminium's tensile strength increases, another advantage over steel (which gets brittle at low temperatures). For envelope systems that must endure cold winter and hot summer temperatures without losing its strength, that is an important property. When exposed to air, a layer of aluminium oxide forms on the surface, protection it against further corrosion. Aluminium is a very soft material, which makes it easy to extrude, the reason there are so gigantically detailed gutter systems.

Manufacturers of aluminium systems use different alloys. BOAL, one of the largest producers and suppliers of aluminium profiles used, based in Westland, Netherlands, uses the alloy EN AW-6063 T66 (van der Ende, K. [BOAL], personal communication, January 18, 2023). This is a widely used extrusion alloy, suitable for applications requiring only modest strength properties. Parts can be produced with good surface quality, suitable for many coating operations. Its density is 2,700 kg/m^3, double that of steel! The data is derived from an alloy data sheet of aluminium supplier Nedal Aluminium, in appendix 1 (Nedal Aluminium, 2017). Aluminium profiles can be made thicker at the top/bottom and at the sides to respectively handle more vertical and horizontal forces, such as deck washing machines, people working on the deck, or wind loads.

glass

Horticultural glass panes provide the characteristic transparancy of greenhouses, which allow crops to get lots of daylight without being exposed to the outdoor weather. It is often four millimeters thick and is four to seven times stronger than regular float glass because it is heat tempered. This increases safety too; upon breaking it shatters in lots of small pieces that cannot damage either human or crop. Other dimensions depend on the rod sizes, column span (gutter direction), and trellis span (perpendicular to gutter direction). Its translucency can be increased by using low-iron glass or applying an antireflection (AR)coating (Dutch Greenhouses, n.d.-c). Due to the standard greenhouse dimensions (trellis size of 4,500 mm and bay size of 4,500-5,000 mm), glass panes have a center-to-center distance of 1,125-1,250 mm, respectively. Exceptionally, 1,000 mm occurs when a 5,000-mm bay is divided into five; this is economically inefficient because the use of additional deck rods does not outweigh the load reduction on the panes. Usually, the glass width is a slightly smaller than the center-to-center distance, as rods take up some space in width.

4 mm thick panes were instituted by the HaagUnie (an insurer of greenhouses) after a violent storm in January 1990 caused an enormous amount of damage to constructions with thinner panes. Horticultural construction requirements are usually tightened after extreme weather, such as severe storms, or disproportionate snowfall. Such events identify structure weaknesses, which are costly for insurers (van der Knijff, A. [Handelsonderneming A.C. van der Knijff B.V.], personal communication, December 10, 2022). A bay size of 4,500 mm is the current standard; seemingly the maximum of the ever-increasing bay sizes. There have been experiments with a 5,000-mm bay size, but these are prone to glass breakage and structural damage. As the number of deck rods remains the same (for minimal light interference), panes covering larger spans cannot withstand loads that big, especially in bad weather conditions (van der Knijff, A. [Handelsonderneming A.C. van der Knijff B.V.], personal communication, December 10, 2022).

In the horticultural sector, innovations are constantly made to maximize light incidence and light quality, two start-up start-up ideas are discussed (van Meurs, B. [Koppert Cress], personal communication, January 10, 2023). The first start-up, BBBLS, applies a deck system where foam bubbles can be sprayed between two sheets of glass. The dynamic system can increase insulation value by a factor of ten and diffuse sunlight. The start-up has built four greenhouses in Norway, the largest has been successfully growing tomatoes for three seasons. In the Netherlands, they test at Koppert Cress. Soap is washed away with water; both can be completely reused. Using green electricity, the system is CO_2 neutral (Koppert Cress, 2021a). The second start-up, PAR+, has developed a sprayable coating that converts the unused spectrum of global radiation into photosynthetically active radiation (PAR). Thus, ultraviolet light is converted by the coating into usable wavelengths for plants. In addition, the coating diffuses incident light, preventing sharp shadows and creating a more even light level throughout the greenhouse. The proven result: an eight to ten percent increase in crop yield (and thus commercial profit) (Koppert Cress, 2021b).

installations

A common way to generate power and heat is a combined heat and power (CHP) system. It uses natural gas efficiently and provides three resources. First, combustion generates electricity, which can be used to power other equipment. Second, heat is produced, usable to warm heating water. A by-product is CO_2 that can enrich greenhouse air. A CHP provides (indirectly) three of five necessities for photosynthesis (light, temperature, and CO_2), and thus is an efficient horticultural asset (Dutch Greenhouses, n.d.-d).

High temperatures are detrimental to photosynthesis and lead to losses of sugars for maintenance and repair of plant tissues damage. To cool air, two systems dominate the market. One is pad and fan cooling, in which warm air is drawn in by a fan, cooled as it moves across a wet pad, to be then dispersed again. The other is high-pressure atomization through tiny orifices. Provided the air is hot enough, these tiny droplets are absorbed by the air, chilling it through evaporative cooling (Dutch Greenhouses, n.d.-e).

Low temperatures are equally harmful; cold reduces enzyme activity in plants, interfering with nutrient uptake. Traditionally, a central gas boiler heats water that is distributed with a pump and valve system. Another old-fashioned way is hot-air heating, running on natural gas, diesel, or petroleum (again, not eco-friendly). Modern greenhouses use a CHP to heat water that circulates in a network of pipes. Recent projects see multiple greenhouses sharing geothermal systems (Dutch Greenhouses, n.d.-f).

Horticultural crops thrive at a CO_2 concentration of 800 parts per million (ppm). As outdoor air contains 350 ppm, air must be enriched in one of three ways. 1) combustion of natural gas (1.8 kilograms CO_2/m^3, usually in a CHP), 2) pure liquid CO_2 supply, or 3) fossil fuel combustion with air heaters (least eco-friendly). Concentration decreases from source to sink; CO_2 leaks at windows must be minimized. Gas with harmful components cannot be used, so natural gas is the standard (Dutch Greenhouses, n.d.-g).

Greenhouses must be ventilated to get rid of hot air and airborne contaminants, therefore the deck has ventilation windows, situated in the ridge to utilize thermal flow. The dimensions of vents determine the air renewal capacity. Windows open with a push/pull mechanism connected to the pane and trellis. Two- and four-pane vents are placed in the normal grid (their center falls above a trellis), one- and three-pane vents are shifted half a pane so that their center falls above a trellis as well (Dutch Greenhouses, n.d.-h).

Photosynthesis requires (sun)light, which can be supplement with artificial light when it is not available in amounts considered sufficient for commercial crop production (less than 4.5 hours of sunlight per day, common in high/low altitude regions or during overcast weather). The majority of greenhouses use SON-T lamps but are starting to mix them with or replace them with LED lamps. 100% artificial lighting regimes are not yet economically feasible compared to hybrid schemes (Dutch Greenhouses, n.d.-i).

foundation

As most greenhouses are lightweight structures, their foundations are elegant. With steel base plates, columns are connected to concrete or steel dollies that transfer pushing and pulling forces to the ground. Dollies are placed in a hole and secured with concrete; those that carry columns to which cross bracing is applied are buried in larger holes, as they transfer higher loads. The bottom horizontal gable rods are supported with thin concrete or composite beams, which rest on concrete dollies (Dutch Greenhouses, n.d.-l). For commerical greenhouses monolith poured concrete is used, which is **absolutely not reclaimable** from the soil unless it is broken apart. An interesting development that makes dismantling greenhouses easier is the replacement of concrete slabs lying on concrete dollies (*figure 4*) with fibre reinforced recycled plastic variant. On the one hand, this increases circularity in the sector, because the plastic can either be reused or recycled; on the other hand, it makes the burden on workers much lower, because the plastic sheets weigh twenty times less per linear meter (van der Knijff, A. [Handelsonderneming A.C. van der Knijff B.V.], personal communication, December 10, 2022).

figure 4: concrete foundation (l) and recyclable fibre reinforced plastic foundation (r) (own, 2022)

insect netting

Growers do not want harmful insects indoor their greenhouses because they could infect their crops with diseases and viruses. On the flipside, they want to keep useful insects such as pollinating bumblebees inside. To accommodate both desires, insect netting cassettes can be mounted on the aluminium frames of ventilation windows. Depending on the mesh's intricacy, it can allow small insects to enter. Of course, the weight they entail must be included in the structural calculations (Dutch Greenhouses, n.d.-m).

An indispensable part of a functioning greenhouse are service buildings: offices, canteens, break rooms, sorting and packing areas, and technical rooms. The latter are often inaccessible to most employees.

For example, irrigation rooms, where nutrients and/or fertilizers must be perfectly mixed to meet crop needs, should only be entered by cultivation specialists. Boiler and CHP rooms should either be separated from the greenhouse or separated with fireproof traps to ensure safety (Dutch Greenhouses, n.d.-n).

films

There are two types of film that are applied in greenhouses: first, there are transparent films which replace glass in polytunnels (**these are not glasshouses!**). Transparent films substitute glass and thus must have a very high light transmission. Other desirable glass properties also apply to films: heat transmission, high strength, and longevity. The most commonly used film for polytunnels is polyethylene (PE) because it offers many good properties and is non-toxic. Howver, it must be treated with UV stabilizers to make it last more than a year. Other additives can alter its brightness, diffusivity, colour, and strength (von Elsner et al., 2000). Polyethylene should be supplemented with additives (mineral fillers) or vinyl acetate (VA), this prevents that indoor heat radiates to the night sky and thus reduces greenhouse cooling during cold nights. In addition, films should have anti-condensation and anti-dust characteristics, since plastic films are hydrophobic, water condenses on its surface. This increases light reflection and heat loss, and droplets cause crop damage. Again, added additives can provide better behaviour (Gbiorczyk et al., 2004).

Second, there are bottom films, which are used in all greenhouse typologies. Soil covers are on the floor of greenhouses. Usually they are black (to absorb light) or white (to reflect light), with the task of reflecting as much PAR and/or NIR radiation as possible. The reflected PAR radiates back to the crops, giving them more available light and higher yields. In ornamental crops, high reflection of PAR radiation leads to more photosynthesis. Film with high absorption for NIR radiation keeps this energy in the greenhouse, saving energy (Mohammadkhani & Sonneveld, 2003).

Different film materials can be laminated via coextrusion. Inner layers contain desired properties, outer layers have anti-wear properties to increase the films lifetime (Verlodt & Waaijenberg, 1999). Films have been developed to admit more desirable and less undesirable portions of the global radiation spectrum. As more was understood about photosynthetically active radiation, a new generation of foils has been invented: photoluminescent films. These decompose the PAR spectrum and allow red and blue light to pass through, giving the film a pinkish appearance. Filtering the light ensures that plant saturation happens with the optimal colours, and not with less utilized green light (Schettini & Vox, 2010).

sheets

Plastic sheets are used where shade rather than sun is required, or simply only a canopy is needed (this is financially feasible as plastic sheets are usually cheaper than glass). The wide variety of options offers several advantages through added additives and coatings to influence light transmission, durability, and condensation behaviour. An advantage that sheeting holds over glass: basically, every mechanical and optical property of plastic can be freely modified by using the right additives (Hemming et al., 2004). Single-walled flat sheets are not common to be found in horticultural constructions due to their relatively low strength and stiffness - they are only useful in (a financially unfeasible) thicknesses or small sizes. Therefore, corrugated, trapezoidal, and zigzag plates are manufactured to acquire more strength/stiffness in plates with less material requirement then a solid thick sheet would. In constructions that require insulation, double-walled systems are used, in which various insulation materials can be incorporated.

Common sheeting materials are PVC (polyvinyl chloride), GRP (glass reinforced plastic), PMMA (polymethyl methacrylate), and PC (polycarbonate). PVC is not environmentally friendly and only found in old greenhouses, no longer in new constructions. GRP is difficult to clean and ages quickly under UV radiation. PMMA is more expensive than glass but has a better insulation value and better transmission for perpendicular incident light, however its fire properties are unfavourable. PC has the highest strength, a high impact resistance, and handles fire better than PMMA, but the light transmission is low due to a higher refractive index (Hemming et al., 2004).

screens

Screens are used to protect crops from excessive sunlight, regulate the growing conditions, avoid the escape of energy and heat, and protect the greenhouse surroundings from light contamination. Depending on the fabric, screens can save energy, diffuse light, shade, or block light. Because they can affect the indoor climate, they are also known as climate screens. Between trellises, they open and close in the gutter direction, supported by wires (on the bottom and on top) that prevent them from moving up and down due to wind suction. Profiles guide the screen motion, driven by a motor. Rubbers prevent any leakage of air, moisture or light between the aluminium profiles and the trellises (Dutch greenhouses, n.d.-j).

When it is cold outside, water in the indoor air condenses against the deck and is discharged through the gutter. This causes the humidity to drop below the desired level. Then (horizontal) moisture screens can be a solution, they prevent moist in the air to get to the cold deck and keeps the moisture level between crops and fabric at the desired level. Aforementioned screens and this moisture screen can be combined to form a combi- or duo screen, other combinations of functions are possible too (Hemming et al., 2004).

Vertical screens are used to close off glass gables, they work with roller screens between columns and are often limited to a two meter height. Common six-meter-high greenhouses thus have three screen sections that can be operated separately. When closed they protect crops from excess sunlight. Besides, they prevent artificial light from radiating outward, as light pollution is prohibited in some regions because it could interfere with the lighting plans of neighbouring farms or disturb the sleep of residents of nearby villages (Dutch greenhouses, n.d.-k).

The research conducted in this chapter has been incorporated in the design of a hybrid urban vertical farm. Now, at its conclusion, references are made to the chapters in which the features identified as important in this chapter have been incorporated into the design.

- The philosophy of a primary and secondary load-bearing structure in the steel structure of a greenhouse has been adopted in the design of huvf modules (p3 module c3 design);
- Comman trellis and bay sizes have been respected in the design of huvf modules to avoid the resulting design being weak and prone to glass breakage (p3 module c3 design);
- Common deck rods with a center distance of 1,125 mm have been used in the design of huvf modules to avoid the design being weak and prone to glass breakage (p3 module c3 design);
- As a possible alternative to concrete foundations, the use of fiber reinforced foundation slabs has been recommended to increase the circularity of greenhouse construction (p7 integration c1 greenhouses).

in this chapter

It is important to point out that despite being circular, a greenhouse cannot be dismantled into every single part because some steel components are welded together. And that is a good thing. Why? That is explained in the first paragraph, the second paragraph discusses how a microsolution can save time and energy.

welded components

There is one rule in greenhouse construction: **do not weld on the construction site.** Hence, all welded components are finished in the factory (trusses, columns with foot plates, columns with purlin corners, etc.), and on the building site they are connected to other (steel) elements mechanically. You cannot disassemble a trellis when demolishing a greenhouse. However, this is good, because a trellis will always be reused as a trellis (in a horticultural context). And it is easier to keep track of 100 trellises than it is of 200 hundred girders, 2,000 diagonals, and 200 end plates, and 100 mid verticals. How welded components around a midfield column (midfield column with a gutter plate welded on top, two trellises bolted to it, and two gutter consoles with a gutter snapped into them) can still be disconnected from each other is shown in *figure 5*.

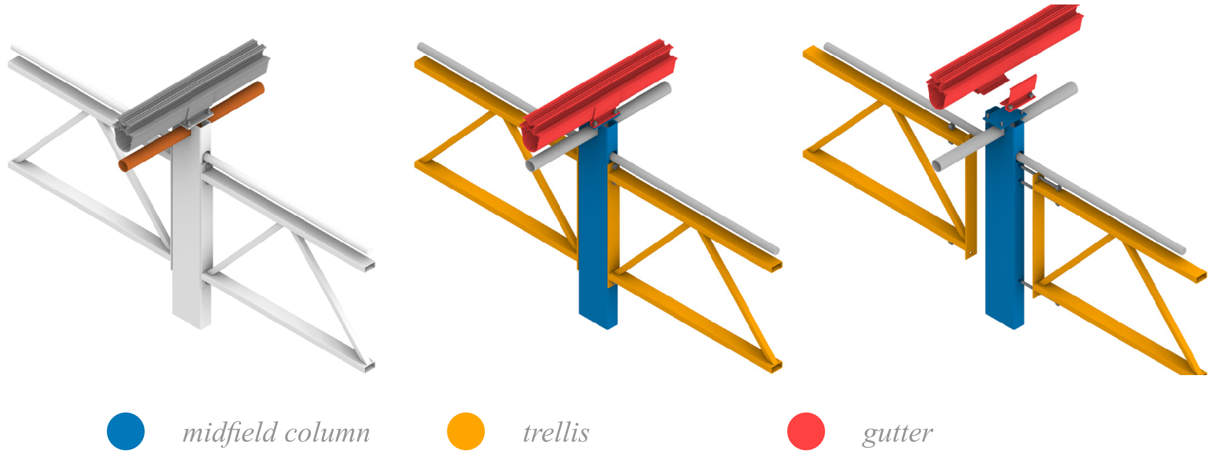


figure 5: circularity and demountability of connected welded steel components (own, 2023)

ungalvanizing or zinc spray?

Conventionally galvanized steel is first ungalvanized before it can be welded and regalvanized. To omit the energy-intensive de/regalvanizing processes, a microsolution can be used: zinc can be sanded away in areas of future welds, than new welds can be made, and then a zinc spray can be used to protect the exposed area. This saves, per kilogram steel, 5.3 MJ on galvanzization (0.33 kg CO_2-eq) (Galvanizeit, n.d.).

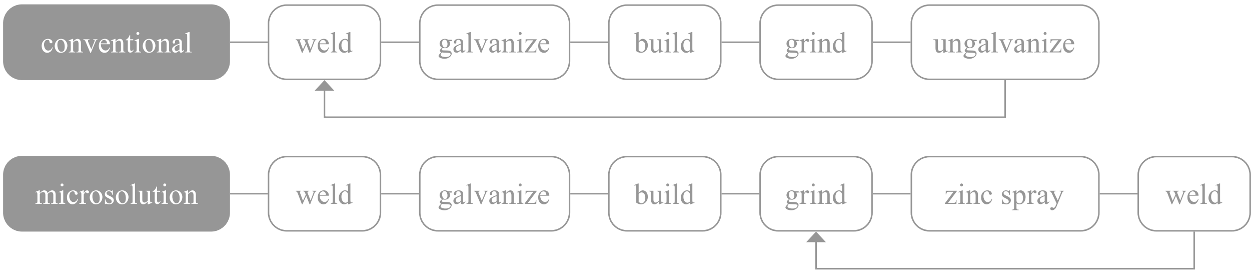


figure 6: conventional galvanizing versus a faster, energy-saving microsolution with zinc spray (own, 2023)

in this chapter

Greenhouses are demolished circularly by dismantling it in the opposite order as it was built. First the installations are disconnected, then glass is recovered from the deck and gables. After, the aluminium is reclaimed. Then the gutters, trellis, and columns are removed. In case of a screw pile foundation they are unscrewed – and the gable foundation is excavated. Every part can be reclaimed, and more importantly, refurbished and reused. This chapter adresses the reuse of steel, aluminium, glass, and installations.

steel

To decide whether or not steel is worth storing, repairing and reselling, greenhouse demolishers check to see if it looks good to the eye. If it does, it is stored for reuse and resale. If it is rotten and/or has a lot of rust on it, it is disposed of as scrap metal. Dirty and slightly eroded steel can be restored by sanding it. In fact, galvanized steel is always still in perfect condition, demolition projects where galvanized steel becomes available are almost always accepted. The strength of steel itself does not decrease during its lifetime; the strength of an entire component may decrease due to deterioration. If the quality of the parts is adequate, the strength is typically satisfactory. Steel that met past structural requirements may not meet new strength requirements by the time it is available to enter a second life. In addition, spans have increased over the years, so sections produced for short spans are simply no longer adequate (van der Knijff, A. [Handelsonderneming A.C. van der Knijff B.V.], personal communication, December 10, 2022). Nowadays, trusses must be made of box sections, so any non-box section (often U-profiles) discovered in trusses are disposed of as scrap or reused in non-horticultural small-scale steel constructions. Greenhouse demolition contractor van der Knijff always checks that trusses have aeration holes through the end plates and columns, which is necessary to prevent truss rot. Previously, aeration holes were not made, and galvanizing fluid remained in the trusses when they were welded shut to end plates. Over time, this caused rust and rot, deteriorating the structural quality of trusses to the point where they were no longer eligible for a second life. Thus, for trusses to be reusable, aeration holes must be present.

In modern greenhouses, steel is galvanized, a prevention against oxidation. Galvanized steel can be cut, as long as the released non-galvanized part is treated with zinc spray to prevent oxidation and rotting of that surface. The same applies to gable columns, to which many elements are welded (aluminium glass bars, rainwater drains, etc.). Such a column can be reused in a new greenhouse, as long as the exposed ungalvanized surfaces that are released after stripping the column are treated with a zinc spray or paste. Recently, zinc-magnesium profiles have been developed; made of a material cheaper than steel with the properties of galvanized steel, as zinc is one of its two main ingredients. Application of this material saves transportation costs from steel plant, to galvanizing plant, to construction site (it allows direct transportation from steel plant to construction site). Moreover, machining zinc-magnesium, colloquially known as magnelis, is especially easy because any released surface is already protected from corrosion (Duijnisveld, R. [Duijnisveld], personal communication, January 18, 2023).

Van der Knijff identifies a trend; in the past, steel AP gutters were multi-purpose. Different deck systems could be connected to simple steel gutters with aluminium connection profiles. Today's aluminium gutters with integrated rebates can be used only for one/a few specific deck systems. In addition, current aluminium gutters require product-specific rubbesrs, clamps and accessories, which may no longer be available at the end of the greenhouse's life cycle. Such accessories are less robust and not reusable after disassembly.

The unavailability of such small parts can hurt the reuse of complete aluminium gutter and deck systems (van der Knijff, A. [Handelsonderneming A.C. van der Knijff B.V.], personal communication, December 10, 2022). Concluding, steel can be reused provided it is not rotten, meets new structural requirements, aligns with modern regulations (e.g., use of box sections), and is treated with zinc spray after processing.

aluminium

In theory all aluminium is reusable, because it is naturally protected from oxidation and its strength does not decrease. However, over the years structural requirements have increased; while there used to be a separate standard for rebuilt greenhouses (demolished and rebuilt), today every greenhouse (new or rebuilt) must comply with EN13031, the European standard for greenhouse structures. (van der Ende, K. [BOAL], personal communication, January 18, 2023). Thus, reclaimed profiles might no longer be strong enough to be reused. If a profile does comply with new standards, it is the lack of chemical corrosion by to climate inside and outside of the greenhouse that is decisive whether aluminium can be reused; whether it is worth careful dismantling. Also, if connections between gutters, deck, and ridges in an old greenhouses are chemical instead of mechanical, neat dismantling is abandoned and aluminium is disposed as scrap (van der Knijff, A. [Handelsonderneming A.C. van der Knijff B.V.], personal communication, December 10, 2022).

Aluminium rods can be cleaned with a brush and warm water with vinegar, this way the soiling and (little) chemical corrosion will come off (van der Knijff, A. [Handelsonderneming A.C. van der Knijff B.V.], personal communication, December 10, 2022). However easy the disassembly, and however high the quality of the aluminium, some suppliers' systems are a red flag. Alcomij ('s-Gravenzande, the Netherlands) and Alcoa (Berkel en Rodenrijs, the Netherlands) manufacture interchangeable solutions, hence, van der Knijff is keen on dismantling and reselling those. Kubo, Boal, and Havecon systems are greenhouse-specific; thus difficult to reuse and resell, and thus undesired by greenhouse demolishers.

As previously mentioned, rubbers are never reused because they are too stiff; they are always replaced. It is important that the quality of the rubbers is high, to avoid unnecessary leakage of heat and CO_2, as this would unnecessarily drive up the operating costs of farms. The financial and environmental losses of a leaking indoor environment do not outweigh the one-time cost of replacing the rubber (van der Ende, K. [BOAL], personal communication, January 18, 2023). The only aluminium connection that is chemically attached is the gutter console, where gutter elements come together. This must be watertight to prevent water leaks. The gutters meet and are embedded in a bed of foam, which must be applied in a pattern imposed by supplier BOAL to ensure maximum watertightness. Detachment of gutters and gutter shell is possible, but requires some directed brute force, opposed to detachable connections (van der Knijff, A. [Handelsonderneming A.C. van der Knijff B.V.], personal communication, December 10, 2022). In conclusion, aluminium parts can be reused if they meet the standards for new greenhouses, if they have not rotted (chemically corroded) and are not chemically bonded together.

glass

Greenhouses are associated with glass; not surprisingly, it is the envelope and thousands of square metres of it go into a greenhouse. Reusing glass is a great source of energy and cost savings. To van der Knijff's knowledge, the properties of glass do not change during its lifetime, and most growers have no objection to reused glass. In fact, it is preferred: new glass costs €10,00/m^2, reused glass costs only a few euro per m^2.

Glass can be cut and resized to fit reclaimed aluminium systems from greenhouses that had smaller panes (van der Knijff, A. [Handelsonderneming A.C. van der Knijff B.V.], personal communication, December 10, 2022). Cleaning with (organic) detergent is sufficient to refurbish glass and remove dirt, scale and/or algae deposits, possibly with a pressure washer. However, this can only be done if it has been **cleaned regularly** during its lifetime. Luckily, most greenhouses are equiped with a deck washing machine that cleans the deck regularly. When growers chalk their glass year after year in summer (blocking out excessive sunlight) without cleaning it in the winter (when they should be letting in all the sunlight), chalk can etch into the glass. This cannot be repaired after years, and the glass is then discarded and recycled to make new glass.

Often the edges of panes are dirty and scratched spot, this is where they were placed in aluminium. The dirt can be cleaned with an (organic) detergent, for example, or the edge can be put through a machine scrubber. The scratching damage is irreparable, but when that pane is reused, either the edge is placed within aluminium profiles again (thus not impeding light penetration), or the pane is resized (thus the damage is cut off). In conclusion, glass can be reused as long as it has been cleaned over its lifetime in an old greenhouse after each chalk season. Then the accumulated layer of filth is thin enough to be cleaned with an organishce detergement. In addition, buyers of used items prefer much cheaper reused glass.

installations

The installations that van der Knijff recovers when a greenhouse is demolished are send back to their original manufacturer for an overhaul, so his company can guarantee machines will work like new. This does require transportation, but eliminates the need for new machinery and the use of critical earth materials, etc. The original manufacturers of machinery want to ensure the quality of their products, so overhauls are complete and comprehensive (van der Knijff, A. [Handelsonderneming A.C. van der Knijff B.V.], personal communication, December 10, 2022). Screen systems can be demounted, and although the fabrics are often worn, the driving mechanisms can be reused (after possible revision by their manufacturer). All heating pipes that transfer warm water can be grinded at the welds, to be rewelded elsewhere. This way no metal is wasted, only the welding material is sanded away.

The research conducted in this chapter has been incorporated in the design of a hybrid urban vertical farm. Now, at its conclusion, references are made to the chapters in which the features identified as important in this chapter have been incorporated into the design.

- To ease the reuse of steel in the construction of huvf modules, the steel is not ungalvanized and re-galvanized, but is sanded, welded and then treated with zinc spray (p3 module c1 approach);
- The decks/gables of huvf modules are rebuilt with the same pane dimensions as the greenhouse from which they came, so that the damaged edge does not impede light transmission (p3 module c2 design);
- In carbon footprint calculations, concrete, rubbers and PVC strips are considered new instead of reused because reuse is difficult/possible (p6 carbon c1 huvf, p6 carbon c2 case study);
- Positives and criticisms on the sector's circularity were noted during the visit to van der Knijff are used as input for the reflection on the circularity of greenhouses and the sector (p7 integration c1 lifespan).

c4 roadmap

in this chapter

If a greenhouse is to be demolished to be reused there are steps that can be followed. A 10-step roadmap is designed for that purpose, with two possible initiations and eight subsequent steps. This roadmap is a relatively self-contained element of this thesis, but is considered important to show because it provides a guideline on the practical application of the hybrid urban vertical farming concept.

roadmap

The reuse roadmap in *figure 7* can be initiated in two ways, either an entrepreneur wants to build a hybrid urban vertical farm (and wants to safe the costs/energy associated with new materials) and is looking for reclaimed greenhouse parts, or a demolition company has been commissioned to demolish a greenhouse and is looking for a buyer to make careful disassembly of the greenhouse parts profitable compared to raw demolition. On the next page, the ten steps are further explained using the keywords that are in the roadmap at each step. It also explains what the transport vehicles mean and why refurbishment (step 6) can sometimes be skipped, and sometimes not.

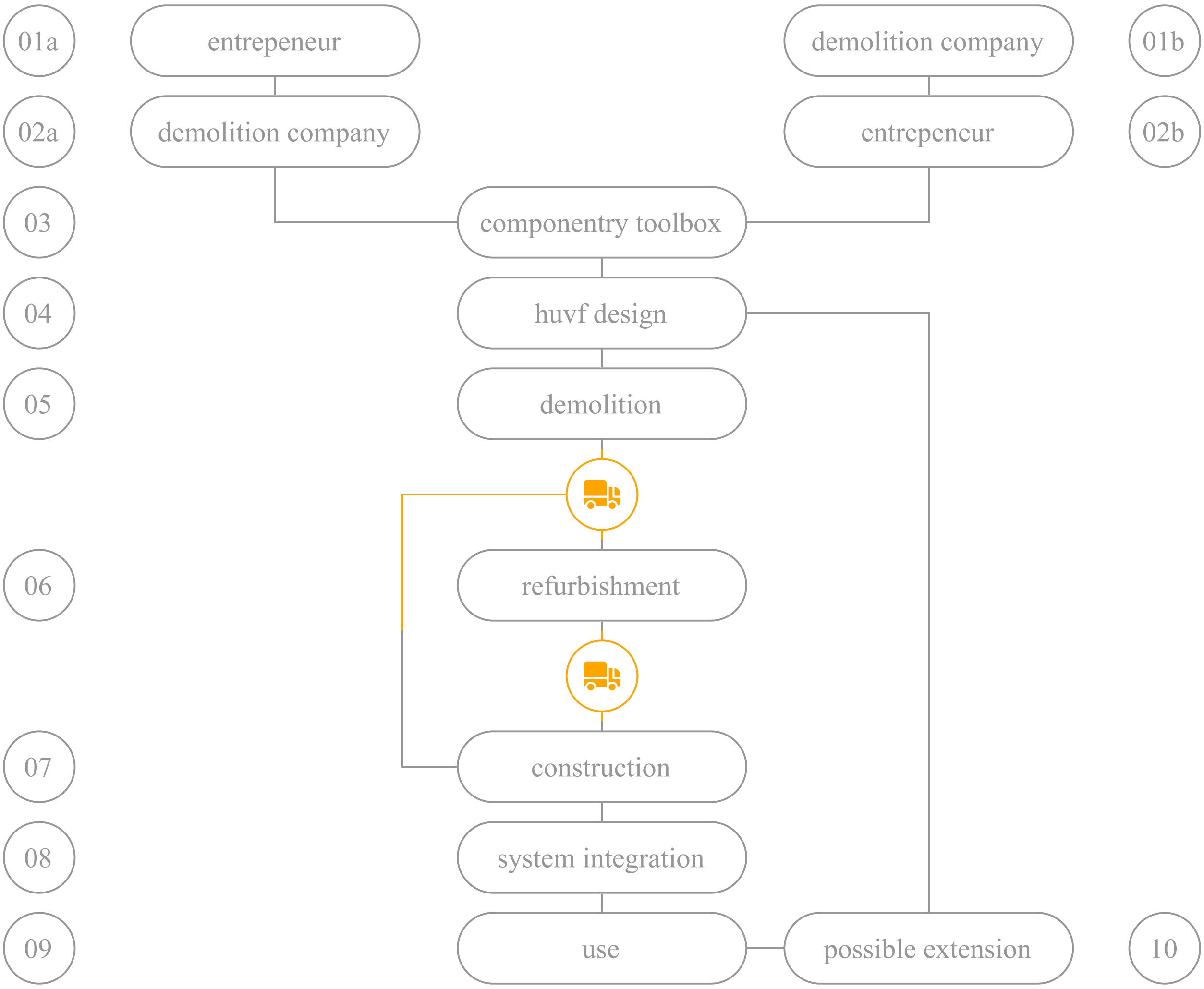


figure 7: reuse roadmap (own, 2022)

step 01a, entrepreneur: an entrepreneur wants commercially cultivate crops on a small footprint whilst minimizing the amount of resources he needs. He chooses to have a hybrid urban vertical farm built.

step 02a, demolition company: to reduce investment costs, the entrepreneur looks for greenhouses that will be demolished. He wants to buy reclaimed materials at a low price from a demolition company.

step 01b, demolition company: the dismantling of an outdated greenhouse is commissioned to a demolition company. Through neat dismantling, parts can be sold afterwards, increasing the project's revenue.

step 02b, entrepreneur: to justify neat dismantling financially, a buyer for the (to be) reclaimed components must be found in advance to agree on a price. The upcoming vertical farming sector might be interested.

step 03, component toolbox: when an arrangement between an entrepreneur and a demolition company is in place, components should be identified (construction drawings, material passport) prior to demolition.

step 04, huvf design: with the toolbox of components, a hybrid urban vertical farm can be designed aiming for a high reuse percentage. If there is a shortage of a component, replacement (new) parts can be ordered.

step 05, demolition: a list of required components results from the design. These must be neatly disassembled to allow reburbishment and reuse. Components should be collected and marked, for easy identification.

transport: preferably, the demolition site is close to the refurbishment facility to save on transportation.

step 06, refurbishment: the demolisher or a third party refurbishes components and assures their quality. If necessary, replacement (new) parts are ordered. Componentry in excellent state goes to the construction site directly, meaning refurbishment can be skipped. Machines are sent back to the factory for overhaul.

transport: preferably, the refurbishment facility is close to the construction site to save on transportation.

step 07, construction: according to the construction drawings for the hybrid urban vertical farm, the structure is built with mechenical connections; no (new) welds, adhesives, etc. Steel, aluminium, and glass are reused in the construction of the huvf. Reusable installations (hvac) come next. Motors, etc. follow in the next step.

step 08, system integration: the innovative growing system can be placed in the hybrid urban vertical farm. Depending on the module sizes, the growing systems can connected and placed next to each other on a rails.

step 09, use: once the hybrid urban vertical farm is constructed, and the growing system is set up, the farm is ready for use. Monitoring the growing climate (light, temperature, humidity, etc.) is essential to grow crops of high and uniform quality in a climate close to the constancy of vertical farms.

step 10, possible extension: given that hybrid urban vertical farms are designed in the same repeating grid as the greenhouses from which they originate, expansion is possible. The connections between two modules can be removed and reconnected to a new module in between, as that will have the same design.

reuse

The research in each part is conducted to answer one or more sub-research questions, which will ultimately help answer the main research question. These sub research questions are answered by means of a certain product, identified in p1 intro c3 research. The results are discussed here.

In p2 reuse one sub research question has been answered, the first one. The question and the approach to finding an answer to it were:

1. Regarding the aspect ".... reused greenhouse components": *"What are common greenhouse components and how can these be refurbished in order to be reusable?"*. It is answered in p2 reuse by means of an overview of common greenhouse components and an approach to refurbish them.

The first part of this question (*"What are common greenhouse components..."*) is answered in c1 components, the second part (*"... and how can these be refurbished in order to be reusable?"*) in c2 circularity and c3 reuse. To provide a concise answer to this question, a list of greenhouse components is developed below, each component followed by the approach to refurbishing it found by reviewing the literature and acquiring methods used in practice by talking to industry employees:

Steel structure: can be disassembled to the level of parts that are already welded together at the factory, and thus must remain welded together. If galvanized, and have ventilation holes to prevent rot, they can be reused without loss of strength. If zinc must be ground away, the released ungalvanized steel should be treated with a zinc spray. This avoids the need for energy-intensive dezincing and galvanizing processes.

Aluminium: can be disassebled without loss of strenght by protection against rust by natural material properties, as long as it has not been affected by chemical corossion from indoor or outdoor climate. Any dirt/light corrosion can be polished off with warm water with vinegar.

Glass: as long as panes have been cleared of chalk annually so that it has not been allowed to etch, then they can be reused without loss of strength and transmission after cleaning with an organic detergent. Provided that panes are reused in an equal or smaller size in an aluminium deck or gable construction.

Foundation: slander gable foundations and screw pile midfield foundations of smaller greenhouses can be reclaimed from the soil, although fibre reinforced plastic foundations are even easier to reclaim. Monolithe poured concrete foundations from large commercial greenhouses cannot be reused, and can only be excavated when the concrete is demolished.

Motors/installations: motors can be revised by their manufacturer and after a check be reused as new (including warranty), installations can be disconnected and reused, mostly without much effort, some require grinding welds apart (e.g., heating pipes).

part three

module

p3

module

in this part

This part, p3 module, consists of three chapters. First, in c1 case study, an exemplary greenhouse is introduced, which serves as a case study for the reuse of its components after demolition. The greenhouse is presented, arguments are provided to support its selection as a suitable case study for this research, and its components are examined in detail (refer to appendix 1). Second, in c2 principles, the fundamental principles of greenhouse construction are explained. All greenhouses adhere to these two main principles, so any greenhouse-like construction utilizing greenhouse components should also comply with them. Third, in c3 design, the available components and construction principles are combined to develop a set of nine modules. These modules can be utilized to construct hybrid urban vertical farm module configurations, which will be further optimized and calculated in subsequent stages of the research.

c1 **case study**

c2 **principles**

c3 **design**

in this chapter

Greenhouses used to be simple, with a limited range of gutters and aluminium decks. Components could be sourced from demolished greenhouses for repairs. However, the industry has evolved, and now each aluminium component can be customized for specific locations on a steel structure. This has eliminated the mix and match economy. To build a greenhouse-like structure, such as a hybrid urban vertical farm, all components must come from the same demolished greenhouses. This chapter presents a single case study that will be further analyzed for the design of hybrid urban vertical farm modules.

industry development

Modern greenhouse components are not interchangeable between greenhouses, now the design of each is optimized for the crop that it cultivates, and the steel construction is dimensioned for site-specific loads and regulations. For each construction, the aluminium extrusion industry offers a variety of integrated gutter and deck systems. These require customized rubbers and connections. Upon demolition, such deck systems are no longer a guaranteed fit with another greenhouse's steel structure (van der Knijff, A. [Handelsonderneming A.C. van der Knijff B.V.], personal communication, December 10, 2022). Greenhouse constructions are calculated with software (e.g., CASTA). It generates a structurally sound design with flat junctions between columns and trellises (equal dimensions) . Those are needed for seamless connection of climate systems (e.g., screens) (van Leeuwen, M. [VB], personal communication, December 05, 2022). The likelihood that two greenhouses have columns and trellises of equal size is small, so the structure and climate systems cannot be reused in combination unless growers accept leaks in their screens (unlikely). Due to the differing systems only reclaimed componentry originating from one greenhouse can be used to rebuilt a new structure, an example being a hybrid urban vertical farm. Smaller greenhouses can provide componentry for smaller hybrid urban vertical farms, whilst bigger greenhouses can fulfil the demand for multiple, or one big one. If multiple phases of a greenhouse are built by the same consortium of companies interchange of components may be possible between the different phase. When consortia differ or change, it is most likely not possible.

reason for a case study

The steps that need to be taken to enable reuse of greenhouse components are the same for each project, but the design that results from it is different in detail, due to the different dimensions of each greenhouse's construction. To keep this thesis simple to follow, a case study greenhouse unpicked to get a fixed set of reusable components. The case study greenhouse is MightyVine phase 3 in Chicago, Illinois, the United States of America. MightyVine is a company that cultivates tomatoes on a footprint of nearly sixty hectares. The company partnered with Royal Pride Holland, a company specialized in growing flavorful tomatoes. MightyVine offers two varieties of tomatoes that cannot be found anywhere else in the United States of America (MightyVine, 2017). The greenhouses operate a hydroponic drip irrigation growing system, which uses only 10% of the water from tomatoes grown in the field and prevents fertilizer from entering surrounding bodies of water. In 2019 the existing two greenhouses were connected to a new third greenhouse, and at that time the construction a phase 4 was already planned. VB led the design and project management of phase 3, and that role was extended for phase 4. The existing phases were constructed by Havecon, but due to different system preferences between VB and Havecon, phase 3 is been built structurally independent: the new and old part are connected by a corridor only. Naturally, due to a reduced wind load on the sidewall facing phase 2, its structure is dimensioned more slender than usual. The (old) east sidewall of phase 2 that faces the (new) west sidewall of phase 3 was kept intact.

To make phase 3 constructively independently, a row of (phase 3) columns is placed right next to a row of phase two columns. This wall facing phase two does not contain cladding (glass or polycarbonate), only the north, east, and south gables and the deck are covered with common envelope materials.

argument for this case study

VB has extensive experience in designing and managing the construction of various greenhouse types, simple and complex ones. For this thesis, a case study of repetitive construction is chosen, which allows for an understandable documentation of components (preventing a long list of a-thousand-and-one post processed columns that are essentially the same). The consortium that constructed MightyVine phase 3 consisted of various companies based in the Netherlands, including Duijnisveld (steel), BOAL (aluminium), PB Techniek (growing systems), Gavita (lighting), Priva (climate control), and Mountain High (construction). Phase 3 was completed in 2019, phase 4 was in 2020, allowing for seamless continuation of greenhouse systems between the two phases.

The design of the greenhouse in this case study is more generic compared to other greenhouses worldwide due to the absence of particularly slender structural elements and the planned connection to phase 4. This generic design is advantageous for the development of the hybrid urban vertical farm. The consortium members' expertise in Dutch greenhouse construction further strengthens the argument for choosing this case. Additionally, the absence of non-standard cross-sections simplifies the reuse methodology, again avoiding an extensive list of essentially identical components. The author's employment at VB provides ongoing access to construction drawings, order lists, and contacts with relevant parties, ensuring comprehensive research material.

The original order lists for steel, aluminium, and glass are included in appendix 2a, 2b and 2c respectively. Together with the original construction drawings, included in appendix 3, all the components that were used to build MightyVine phase 3 were unpicked and tabulated, that table is included in appendix 4.

figure 8: MightyVine phase 3 under construction (VB, 2019)

in this chapter

There are two main principles in greenhouse construction, first, a repeating grid is used and second, there are established ways to absorb wind loads. Both principles must be integrated into the design of a greenhouse-like structure, such as a hybrid urban vertical farm module, to ensure that it is capable of reabsorbing wind loads in a rebuilt form. If not, component reuse becomes impractical. This chapter first discusses how a greenhoude grid works and the implications for reuse. It then illustrates how greenhouses absorb wind loads.

grid

Greenhouses are built on a grid in which the structure repeats itself, except along the gables where the structure is sturdier to handle the higher wind loads. For MightyVine phase 3, a grid of 9,000 (*trellis*) by 4,500 (*bay*) mm is used. Each trellis supports two *peaks*. The terminology is illustrated in *figure 9*. A gable parallel to the trellises is an *endwall*, a gable parallel to the bays a *sidewall*. Each component in a greenhouse is post-processed to fit into the grid, and fit neatly with the components to which it is connected. Thus, when components are reused, it is important that they are reused in the **same** or a **smaller** grid so that they (can be made to) fit. When rebuilding a complete structure, the same grid must be used.

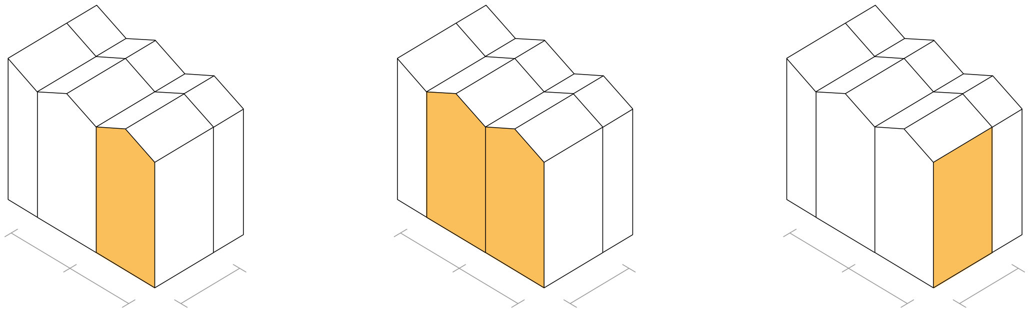


figure 9: greenhouse grid terminology, a peak (l), a trellis (c), and a bay (r) (own, 2022)

wind

Greenhouses are large structures in an (often) open landscape outside the city. The gable is under wind pressure, which is transmitted through the glass and aluminium, through the steel to the foundation. Large wind loads are present on the gable, which is why the gable columns are sized larger than midfield columns. Where gables meet, at the greenhouse corners, the wind pressure is greatest. Here, a strong gable column is not enough, hence half-panes are introduced. The trellis height of a greenhouse determines the length of the half-pane section in the end and sidewalls; the higher the trellis height, the longer the half-pane section, this principle is illustrated in *figure 9*. In addition, the first peak next to the sidewalls is fitted with half-panes. Similarily, the first bay or bays behind the endwalls are fitted with half-panes, determined by the trellis height of thee greenhouse. That principle is illustrated in *figure 9* as well.

consequences

To reuse as many components as possible in a hybrid urban vertical farm, a module must have a grid equal to the original greenhouse. A module is therefore designed as large as one grid section: one trellis by one bay; thus a module from MightyVine phase 3 componentry has a size of 9,000 by 4,500 mm.

A configuration of connected modules must always be a multiple of this grid in any direction. That is the the premise of designing module configurations in p5 optimize c2 fsi. To make a configuration wind-resistant, various endwall, sidewall, and deck envelopes are needed at different positions along the gable and the midfield. The various endwall, sidewall, and deck types, and how they come together in nine various module types, are discussed soon *Figure 9* shows how greenhouses with heights of four, six, and eight meters have four, six, and eight meters of half-panes in the sidewall and endwall, respectively. The case study MightyVine phase 3 has a trellis height of about seven meters, so there are seven meters of half-pane in the endwall and sidewall at the corners, or one-and-a-half bay (one-and-a-half times 4,500 mm, or 6,750 mm).The legend distinguishes between a half-pane sidewall, a transition sidewall, and a full-pane sidewall; this kind of subdivision will be continiously used in this research.

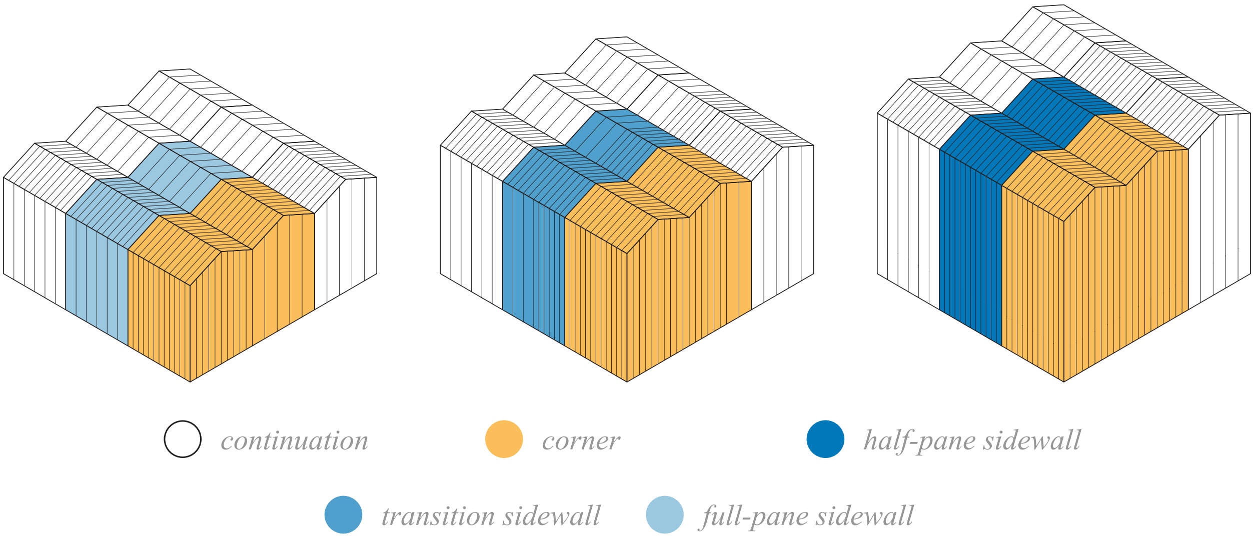


figure 10: dependence of the half-pane section length on the height of the greenhouse (own, 2023)

When viewing a deck from above (*figure 11*) it is noticable that next to the sidewalls one peak is fitted with half-panes, and behind the endwalls one-and-a-half bay is fitted with half-panes (illustrated as if it were MightyVine phase 3). If an endwall is extended, half-pane sections are added *at* the endwall, transition sections *behind* the endwall, and full-pane sections in *the middle*. The same goes for a sidewall extension.

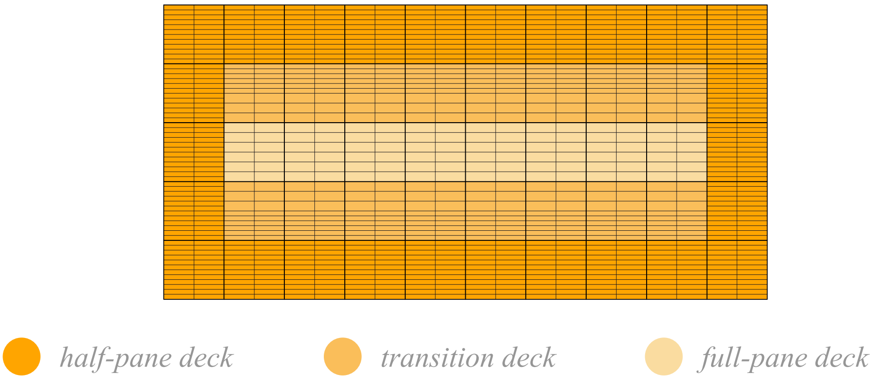
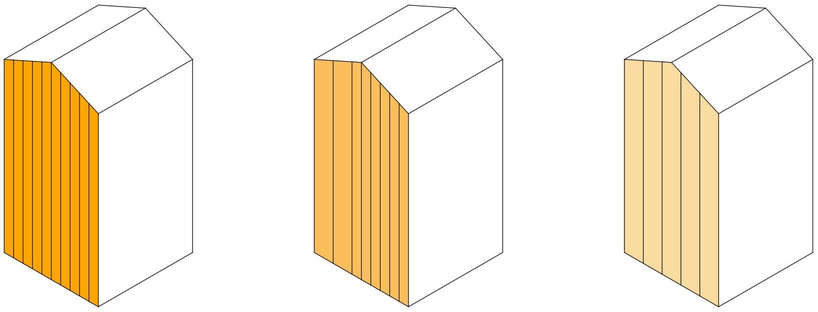


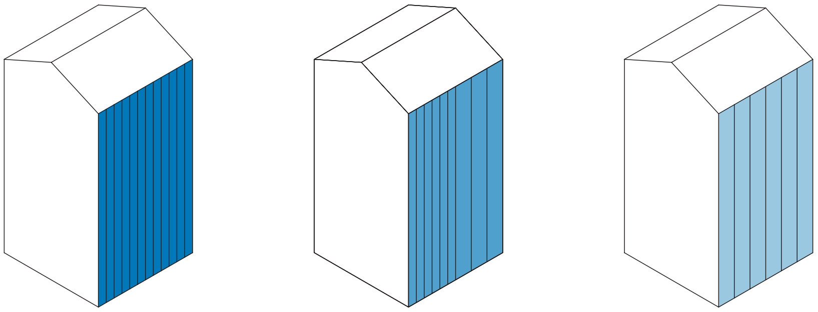
figure 11: top view of a greenhouse deck in which the division of half-panes is visible (own, 2023)

envelopes and modules

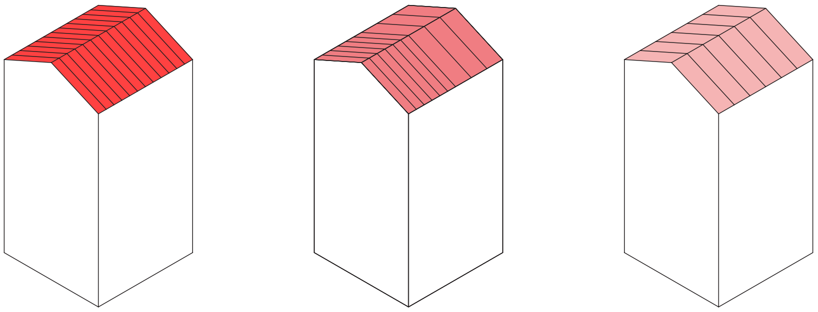
A hybrid urban vertical farm module configuration of twenty modules, does not need a design for each of the twenty modules. Because one-and-a-half peak *or* bay of half-panes is needed for wind transmission in endwalls, sidewalls, and the deck, there are three pane configurations for each of these greenhouse envelope surfaces: *full-pane*, *transition*, and *half-pane*. These envelope types are visualized in *figure 12*.



full-pane endwall *transition endwall* *half-pane endwall*



full-pane sidewall *transition sidewall* *half-pane sidewall*

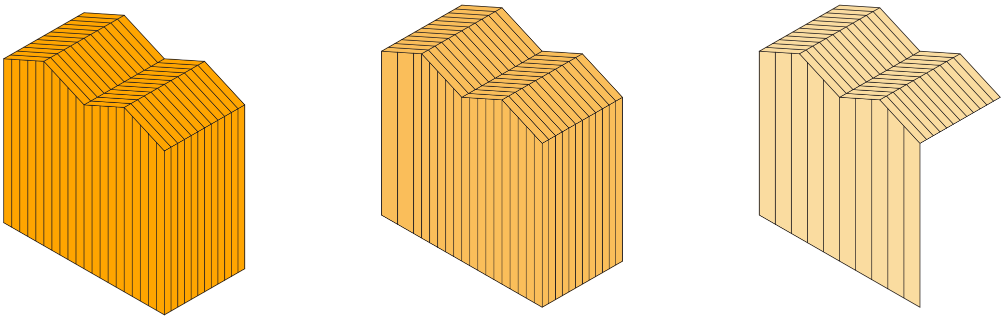


full-pane deck *transition deck* *half-pane deck*

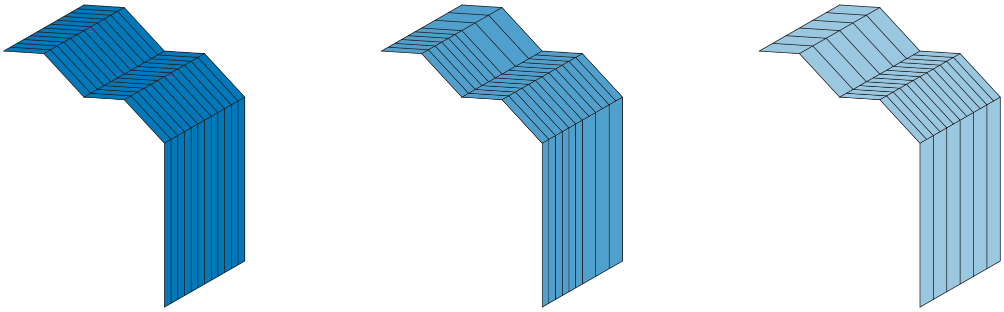
figure 12: nine envelope types for wind load absorption (own, 2023)

The nine envelope types can be combined in nine module types, visualized in *figure 13*. Their names and colors continue to recur in other visuals throughout this research. A bay-link corner occurs when an endwall consists of one module only. As one-and-a-half peak must be half-pane from either corner (three peaks in total), the endwall is filled with half-pane (two peaks, the maximum amount of half-pane peaks possible).

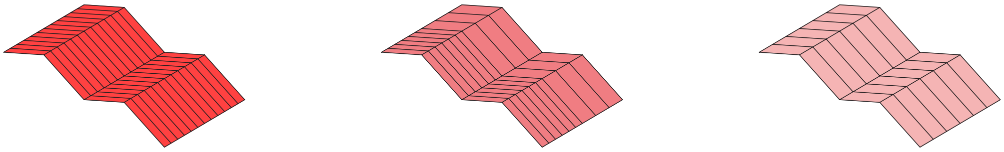
As for sidewall modules, the first peak next to a sidewall is fitted with half-panes; only the second peak of the sidewall modules show the differentiation between full-pane, transition and half-pane sidewall modules. When one midfield module lies between endwalls, a half-pane midfield module is used, so that in total there are three half-pane bays (two times one-and-a-half). When two midfield modules lie between endwalls, these are transition midfield modules, so there are two one-and-a-half half-pane bays and one full-pane bay.



bay-link corner *trellis-link corner* *endwall*



half-pane sidewall *transition sidewall* *full-pane sidewall*



half-pane midfield *transition midfield* *full-pane midfield*

figure 13: nine module types for wind load absorption (own, 2023)

When more than two midfield modules lie between endwals, all but two are full-pane midfield modules, the two near the endwalls are transition midfield modules in that situation. In summary, the requirement is to have at least three peaks or bays of half-glass in each fable; one-and-a-half peaks and bays per corner. If the gable is too short to reach three peaks/bays, then the entire gable will be filled with half panes.

module definition

Now that the module types are known, what constitutes a hybrid urban vertical farm can be defined. A hybrid urban vertical farm module is defined as: *a section of rebuilt greenhouse as large as one trellis by one bay of the greenhouse grid from which its components originate, a module is either 1) stand-alone and equipped with four gables of its own and a deck of its own (a corner module), or 2) part of a configuration and equipped with a number of gables that allow the module to connect to other modules and a deck of its own (an endwall or a sidewall module), or 3) part of a configuration and equipped with no gables and its own deck (a midfield module).*

small module configurations

Module types can form configurations of up to nine modules with only one midfield module. Starting from three trellis-link corners, full-pane gables can occur. Small configurations are visualized in *figure 14*. This illustration shows how modules work together to arrive at a total of three peaks and/or three bays of half-panes, or at least fill the entire endwall/sidewall with half-panes when shorter than three peaks/bays. The center bottom configuration shows how two corner modules work together and can accommodate one full peak (two half-peaks) of full-panes in the middle.

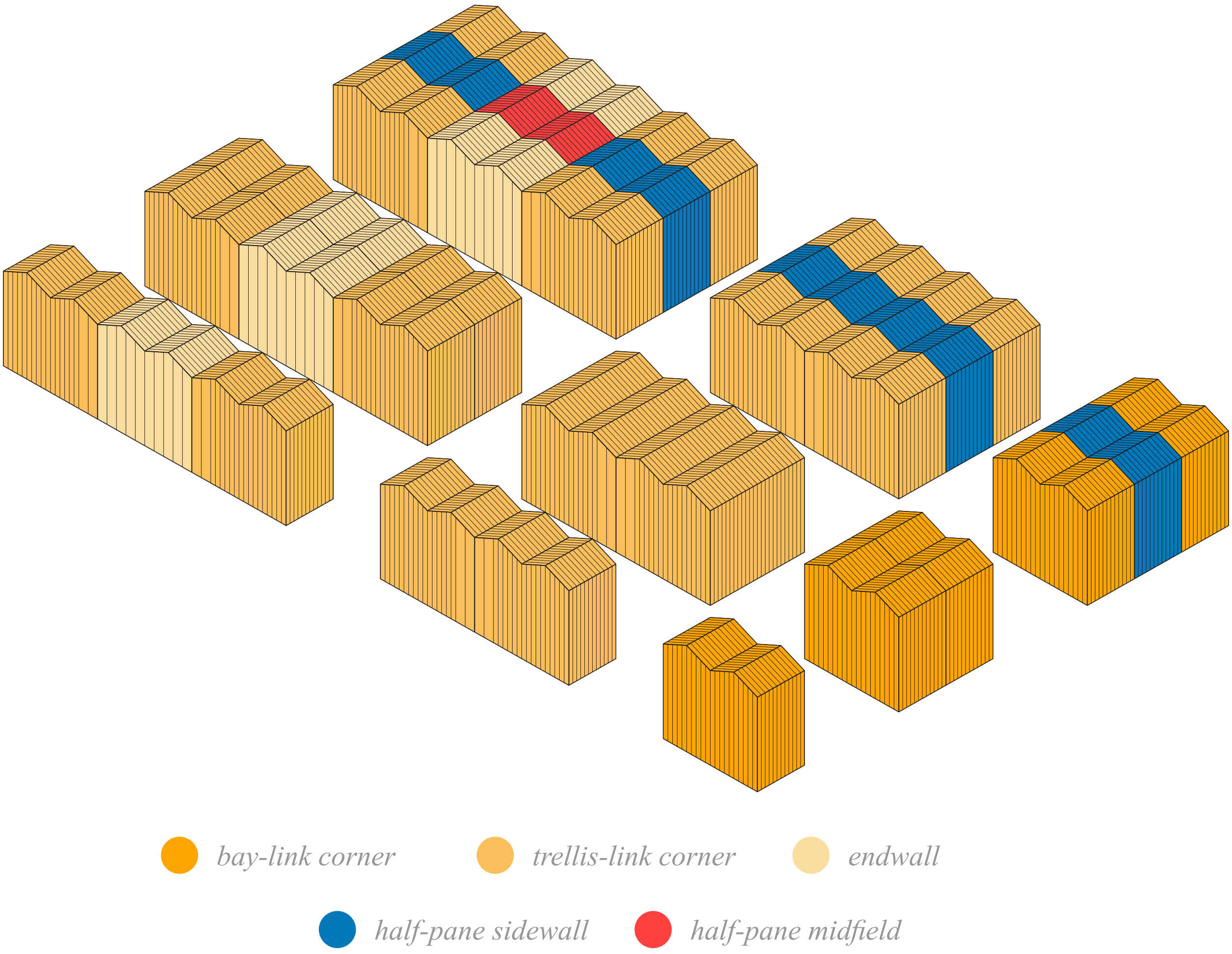


figure 14: module configurations up to one midfield modules (own, 2023)

sidewall module use

Transition sidewall modules occur when two sidewall modules are placed between corner modules. Full-pane sidewalls can occur when three or more sidewall modules are between corner modules; all but the ones next to the corner modules will be full-pane sidewall modules then. These situations, and sidewalls consisting of a single corner module, or two corner modules only, are illustrated in *figure 15*. At all times, as close as possible to twice one-and-a-half bay of half-panes is used, to comply with the wind load absorption principles in greenhouse construction.

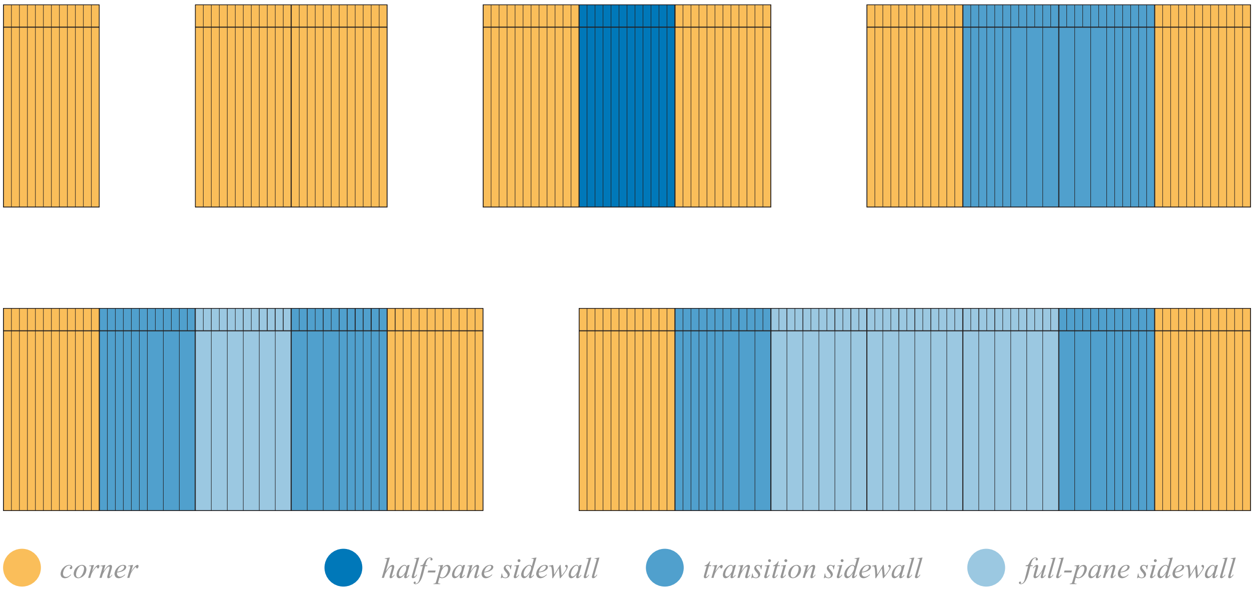


figure 15: use of various sidewall modules (own, 2023)

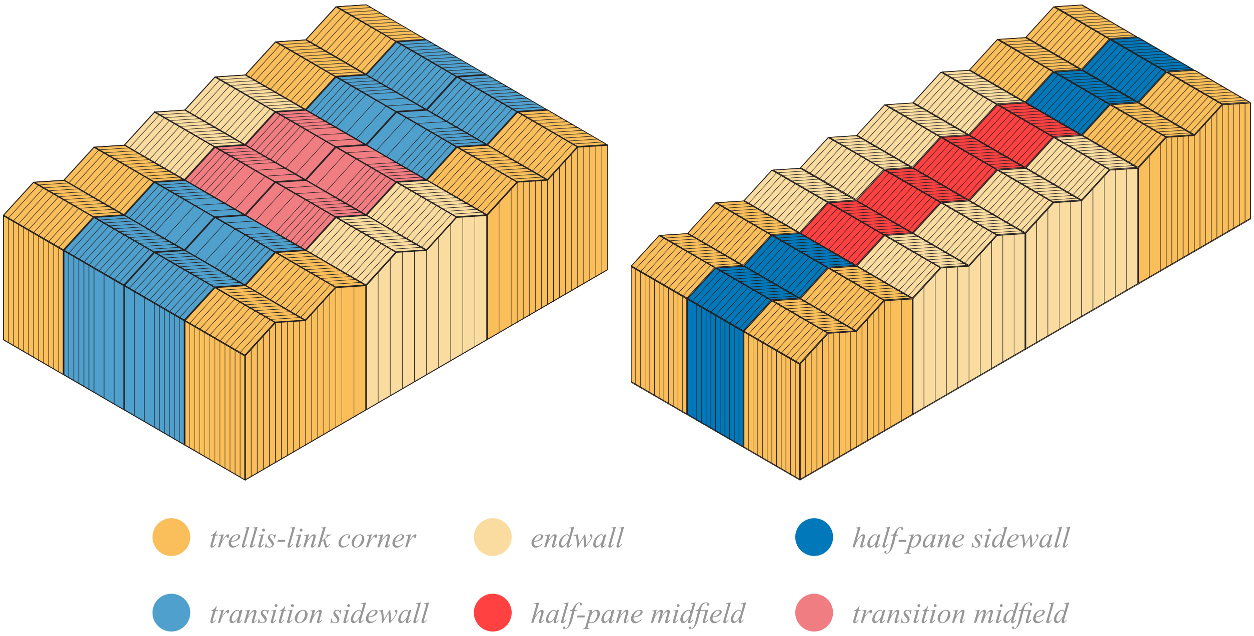


figure 16: module configurations with more than one midfield module (own, 2023)

bigger module configurations

Figure 16 (previous page) shows how three-by-four configurations with more than one midfield module can be made. When the expansion of these configuration takes place in the endwall direction, the midfield modules will always remain half-pane. However, if the extension takes place in the sidewall direction, then first two transition midfield modules will be used. Further expansion in the sidewall direction will lead to the use of full-pane midfield modules between the midfield modules that are closest to the endwall.

three-by-three configuration

Figure 17 shows the smallest configuration that includes a corner, endwall, sidewall, and midfield module, a three-by-three configuration. This is also the basis of the expansion philosophy illustrated in *figure 18*.

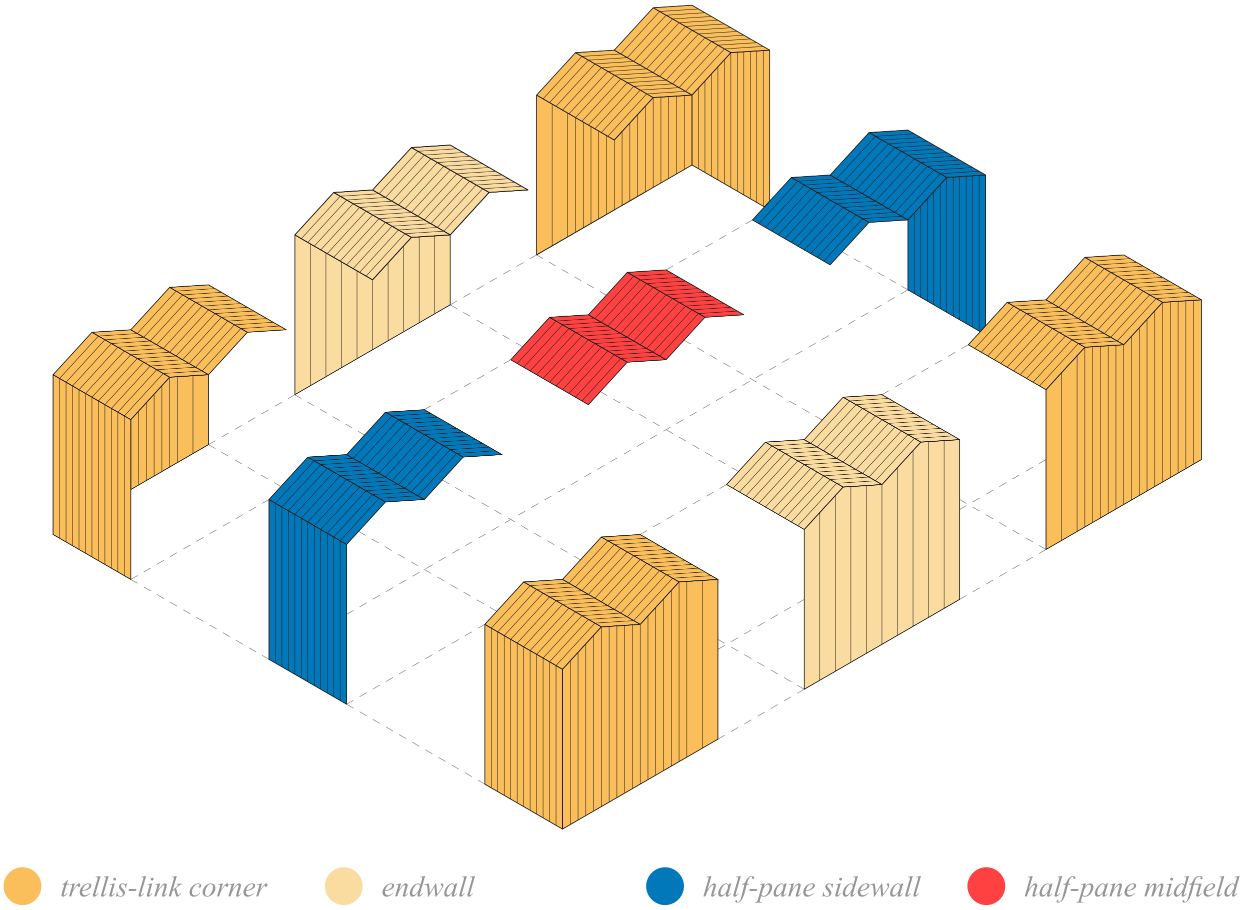


figure 17: smallest module configuration that uses one of each main module type (own, 2023)

When the nine modules for a three-by-three configuration are present (four corner modules, two endwall modules, two sidewall modules, and one midfield module), then within the limits of available components of a demolished greenhouse, the three-by-three configuration can be extended in the endwall and sidewall direction. It is intended that a configuration should not become so large that it no longer fits within an urban context, but in spacious plots the configuration can be expanded to maximize its use a footprint. In *figure 18*, the original modules of the three-by-three configuration are drawn in black and white; extensions in the endwall and sidewall direction, and the modules needed for them, are drawn in with color.

design task

To build any module configuration, within the constraints of available reusable components, all nine module types must be designed. However, the design of each of the differentiations (half-pane, transition and full-pane) within the main module types (corner, endwall, sidewall and midfield) is the same except for its envelope. Hence, in p3 module c3 design, first the steel foundation and steel structure of the four main module types are designed, then the nine different gable and deck types are placed on these to end up with the nine modules that are required to enable any module configuration to absorb wind loads in the traditional greenhouse construction way. The modules will be equipped with all the components also present in the case study greenhouse MightyVine phase 3.

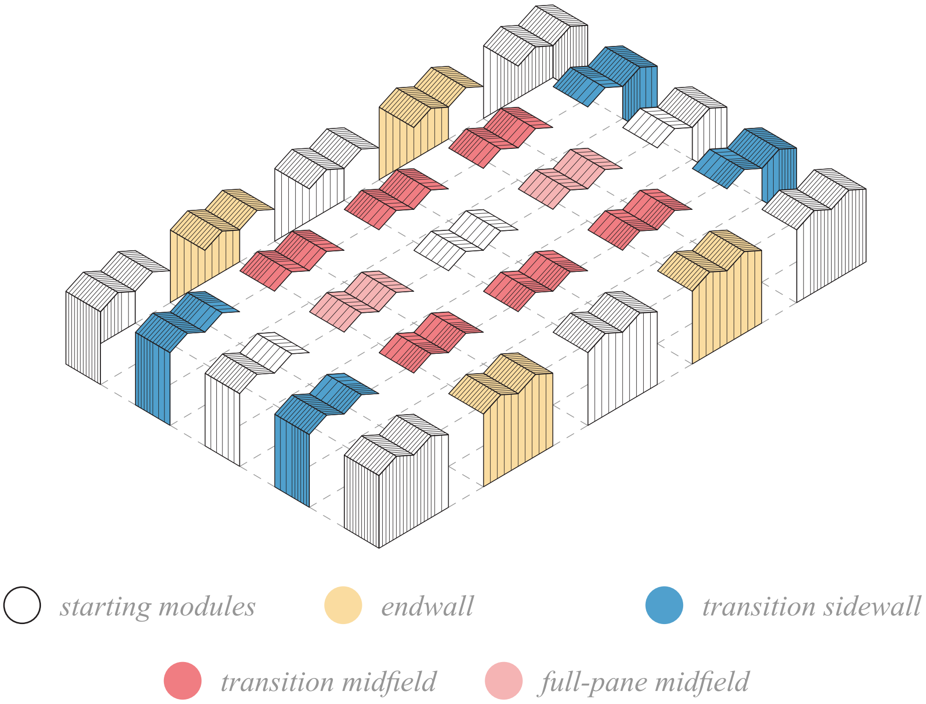


figure 18: expansion (r) of a three-by-three module configuration (l) (own, 2023)

The research conducted in this chapter has been incorporated in the design of a hybrid urban vertical farm. Now, at its conclusion, references are made to the chapters in which the features identified as important in this chapter have been incorporated into the design.

- It can be concluded that in order to construct any hybrid urban vertical farm module configuration with reused components, it is necessary to design nine module types. However, the variation lies primarily in the module's envelope, resulting in the half-pane, transition, and full-pane module types. The foundation and steel structure remain the same for the main module types (corner, endwall, sidewall, and midfield). Thus, initial focus should be on designing the foundation and steel structure for the four main module types. after, the gable and deck types can be added to create the nine modules, that are needed for absorption of wind loads. These modules will be designed with components that can be reclaimed from MightyVine phase 3. This design is made in the next chapter (p3 module c3 design).

in this chapter

Earlier, the principles of greenhouse construction were introduced and before that, lists were compiled of components that will become available when MightyVine Phase 3 is demolished. These two, components and construction principles, are combined in this chapter in the design of the modules. First, the foundation and steel structure of the four main module types (corner, headwall, sidewall and midfield) are constructed in renders with accompanying text. This is followed by the nine variants for the gable and deck envelope.

gable foundation

The gable of MightyVine phase 3 is built on a foundation with three different foundation piles. Endwalls are supported by piles with a diameter of 500 mm and a height of 1,450 mm. As endwall piles are more important than sidewall piles these are used in the corners as well, where endwalls and sidewalls meet. Sidewalls are supported by piles with a diameter of 762 mm and a height of 1,250 mm. Placed on top of foundation piles are beams with a depth of 240 mm and a height of 400 mm. On these the gable construction is built. Beams are made by pouring concrete into a chiseled excavated trench. Concrete beams are not reusable, but new beams could be reusable in the future by choosing fibre reinforced recycled plastic dollies. When a hybrid urban vertical farm is build, it is advised to use equal-sized foundation piles to ensure that the structure can be properly supported again, or a structural engineer should do a recalculation.

midfield foundation

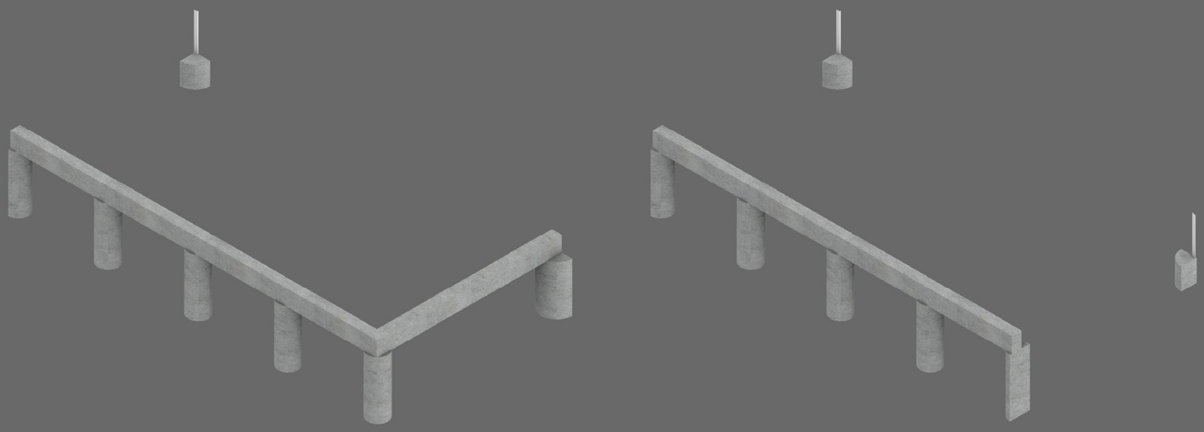
The midfield sections of a greenhouse, and thus of a hybrid urban vertical farm module, is point-founded with low foundation piles with a diameter of 762 mm and a height of 550 mm. While making the foundation, RHS 160x60x3 columns (height of 1,250 mm) on a 200x80x6 mm foot plate are poured level into the concrete base. This column serves as a base for later welding of the 160x60x4 midfield columns that carry the deck, and to which trelisses are bolted. The foundation is laid precisely, so builders can rest assured that its location is correct and the structure build on it will also be level and fitting. In p4 system c3 design, the foundation that supports growing systems is designed **as part of the growing system** itself.

foundation reuse

The foundation of the case study is not reusable because the foundation is poured monolithically and cannot be removed from the ground without demolition, hence any monolithically poured foundation to support hybrid urban vertical farm module configuration will also not be reusable. The 1,250 mm steel columns in the midfield foundation, that are poured into concrete, as well as their foot plates, are also unreusable.

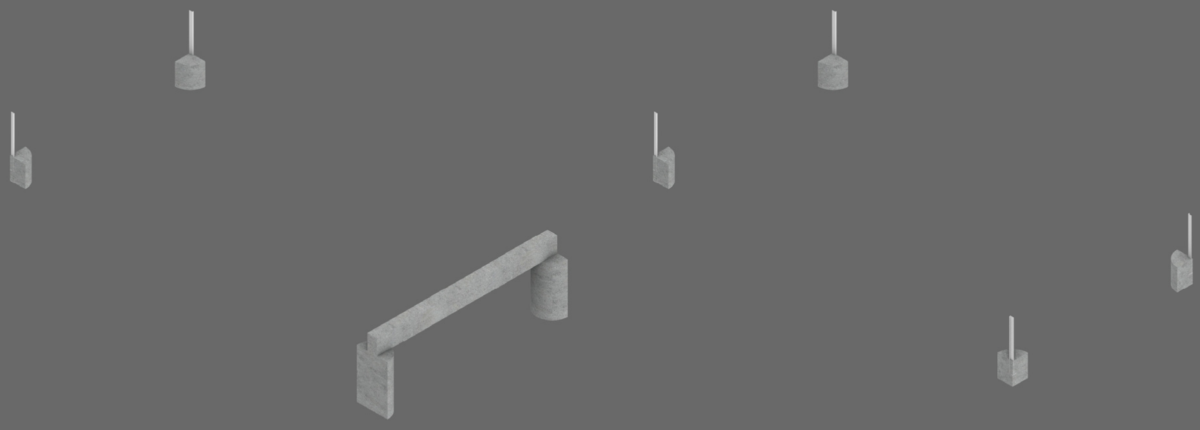
notion: method of illustration

In the isometrics, components at the boundary between modules are split. For instance, in the foundation isometrics, gable foundation piles are divided in half at the boundaries. This splitting approach is also applied to columns, trellises in the steel structure, and gable and deck rods (aluminium) and panes (glass). The purpose is to allocate the appropriate amount of material to each module. When a corner and an endwall module are connected, there is no need for two foundation piles where they meet. Instead, each module contributes half of one foundation pile. Understanding this is crucial for calculating the carbon footprint in p6 carbon. During the comparison, it is essential to assign only the portion of a component within the module's boundary to that module. Otherwise, components will be counted twice, leading to an overestimation of the construction's unsustainability.



corner foundation

endwall foundation



sidewall foundation

midfield foundation

figure 19: foundation of the four main module types (own, 2023)

columns and trellises

Modules, constructed with reused components, need a (steel) load-bearing structure. This structure supports the loads on the gables and deck, transferring them to the foundation. The gables are supported by sidewall columns (RHS 160x80x4) and endwall columns (RHS 200x120x5), each measuring 6,722 mm in height. These columns are placed on a foot plate (250x100x6) installed on the foundation. The midfield columns, measuring 6,378 mm in height, are positioned on point-founded midfield foundation columns already in place. This arrangement ensures that the midfield columns end at the same height as the gable columns. The trellises are connected to these columns, making it crucial for them to align in height. Each trellis is composed of a top and bottom girder, twenty diagonals, a mid vertical, and a mid trellis post. The mid trellis post, equipped with a foot plate, supports the load of a gutter and the deck between two peaks. On both the columns adjacent to the trellis and the mid trellis post, a gutter plate is attached. These plates serve as mounting points for later installation of gutter shells, which will hold the gutter spanning the bay.

purlins

To accommodate the transfer of horizontal loads in the aluminium and glass gable, the gable columns cannot bear these loads at every point. Instead, the transfer occurs once per bay, which is spaced every 4,500 mm. To support the vertical aluminium gable rods, horizontal purlins (u-profiles) are used. The load transfer from the purlins to the gable columns is reinforced by purlin corners (i-profiles). These corners are pre-welded to the gable column in the factory and are then bolted to the purlin at the construction site. However, where an endwall and a sidewall meet, the sidewall purlins are not aligned with the corner column (because the corner column is and endwall column, which is rotated 90^0 relative to the sidewall columns). This misalignment creates a gap that needs to be bridged; hence, slightly larger purlin corners are used there.

bracing

Horizontal forces within the greenhouse structure are transferred through braces located in the roof, gables, and interior. As a general rule, both endwalls contain two braces, as well as both sidewalls. Between the two sidewall modules in which bracing is applied, all midfield modules are also equiped with bracing between midfield columns and in the deck. This creates a continious row of bracing extending from one sidewall to the other. **For smaller greenhouses and module configurations built with reused components, one bracing per endwall and sidewall is sufficient**. Since midfield bracing is shared between two midfield modules or a midfield and a sidewall module, only half of the bracing cross-section is considered for each module in the isometrics in *figure 20*. Bracing can be tensioned using turnbuckles (*figure 20*), allowing safe assembly without fully tensioned bracing. All steel can be reused as joints are disconnected with care.

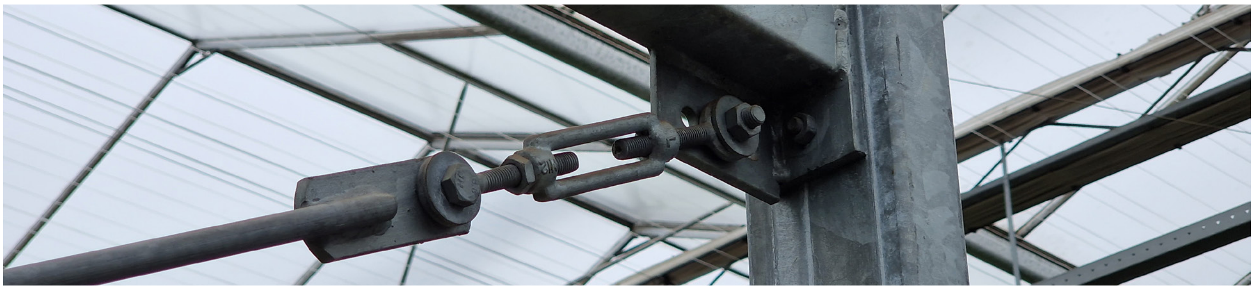
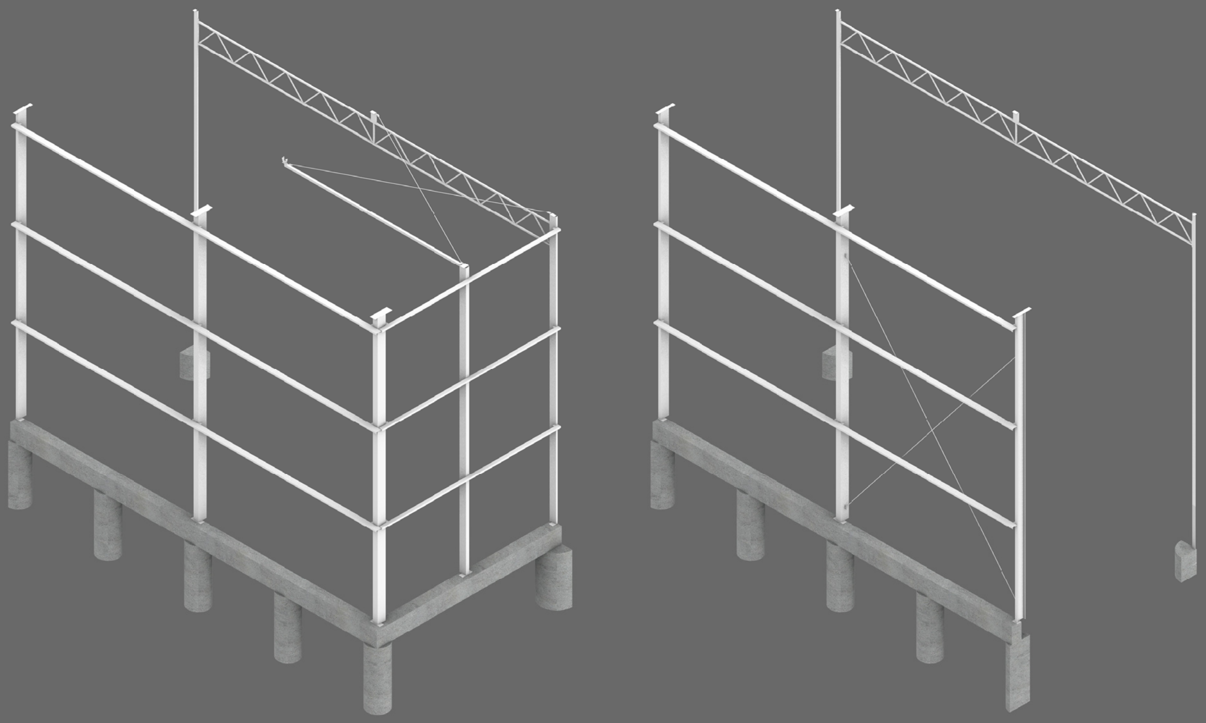
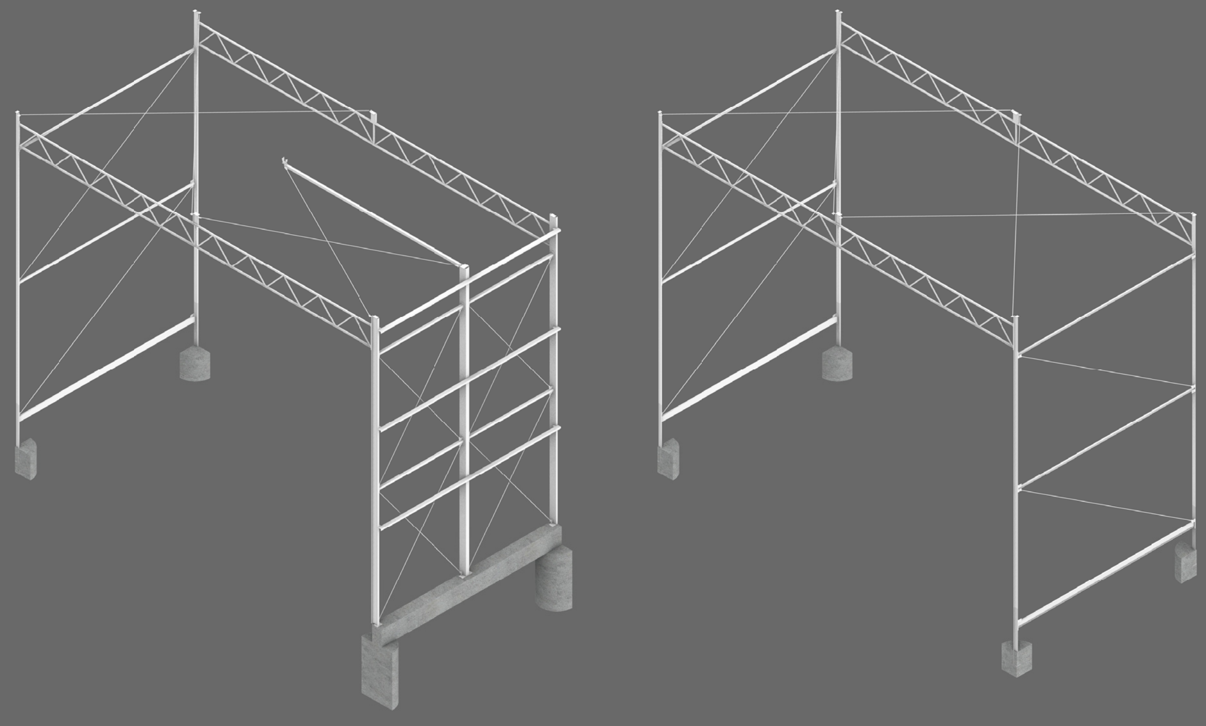


figure 20: turnbuckle (own, 2023)



corner steel structure

endwall steel structure



sidewall steel structure

midfield steel structure

figure 21: steel structure of the four main module types (own, 2023)

The first gutter next to sidewalls is connected to the gable with a pressure beam and bracing known as *first gutter row bracing*. This bracing assists in transferring wind load and suction on the first peak next to the sidewall, which experiences the highest load anywhere on the greenhouse envelope. This particular type of bracing is found only in the corner module and sidewall modules, as depicted in *figure 21*.

endwall gable

There are three modules that include a portion of the endwall gable: the bay-link corner, the trellis-link corner, and the endwall module. According to the principles outlined in p3 module c2, the bay-link corner module is not connected to other modules in the trellis direction. As a result, the entire gable of the bay-link corner module must consist of half-pane glass. The trellis-link corner module, on the other hand, requires only one-and-a-half peaks of half-pane glass, as this length matches the height of the module. Therefore, the last two vertical sections of the glass panes in the trellis-link corner module are full-panes. The endwall module is always situated between corner modules, and its gable therefor consists entirely of full-panes.

Horizontally, all three modules with an endwall gable necessitate the same components, which include approximately nine meters of horizontal stacking profiles. These profiles serve to vertically separate the panes. To prevent the panes from reaching a height of nine meters, which would pose a significant risk of damage due to the immense wind load, the gable is divided vertically. This division ensures that the panes are not excessively tall. Verticallly, the gable construction of the three modules with a portion of the endwall gable differ. The bay-link corner module requires 21 vertical rods, the trellis-link corner module requires 19, and the endwall module only requires 11. The length of the vertical rods varies in the endwall module due to the presence of peaks, which is further explained at the end of this chapter.

sidewall gable

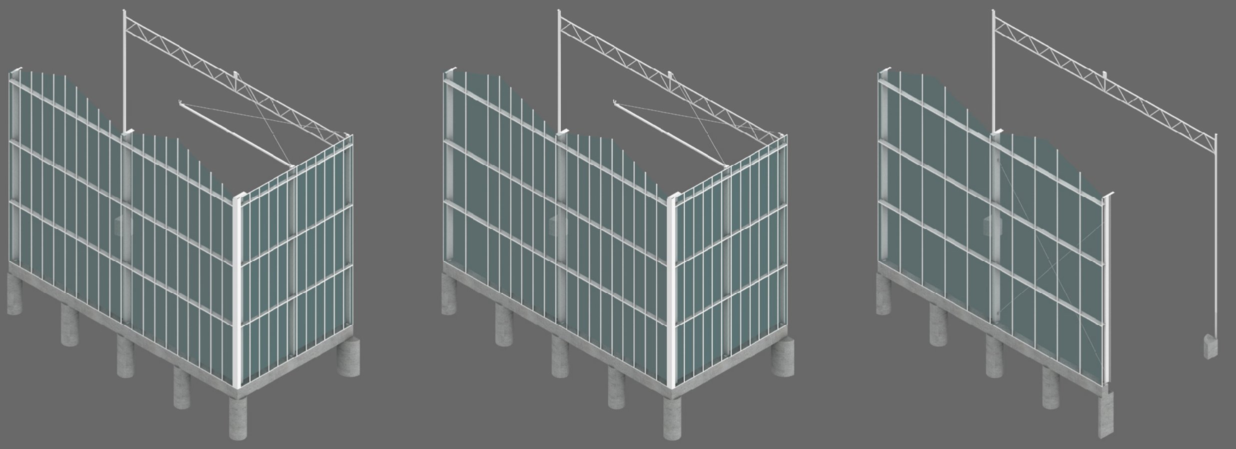
The gable of sidewall modules is identical in all aspects, except for the number of vertical rods required. Unlike the endwall modules, the sidewall gables do not have peaks that cause variations in the lengths of the vertical rods. In the case of sidewall modules, all the vertical rods have a length of 6,741 mm. It is important to note that midfield modules **do not** have gables. However, their isometries are still depicted to maintain consistency in the construction sequence of all the modules.

gable reuse

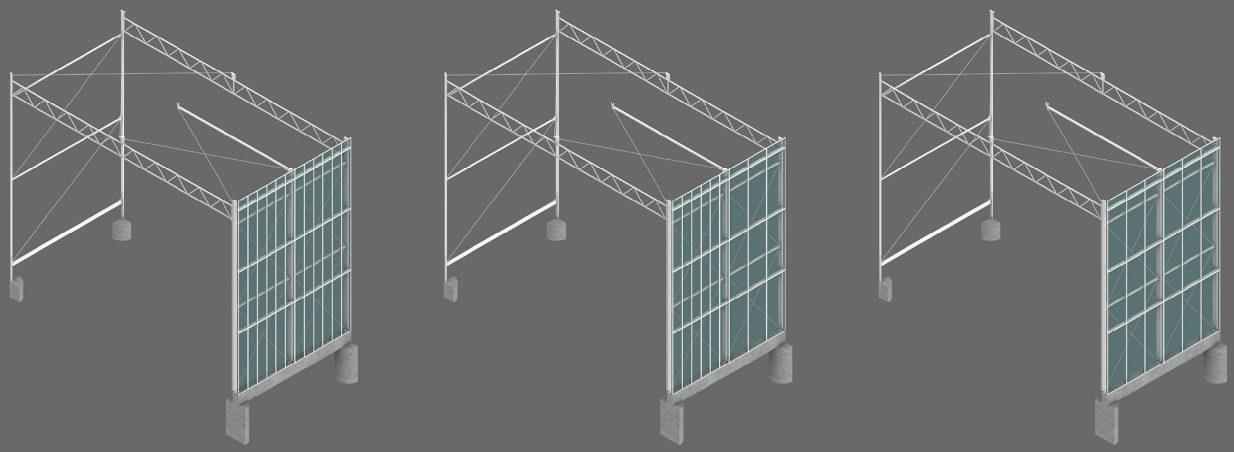
All aluminium profiles used in the greenhouse construction can be reused. However, certain components such as the rubber between profiles and glass, as well as the PVC strips that seal the aluminium profiles, tend to become rigid and brittle over time due to weather and UV radiation exposure. During the dismantling process of a greenhouse, these parts often sustain damage or deformation beyond repair. Therefore, when constructing a hybrid urban vertical farm, it is necessary to use new rubber and PVC strips to ensure proper sealing and functionality of the aluminium profiles. These new components will provide the required flexibility and durability for the rebuild construction.

ventilation windows

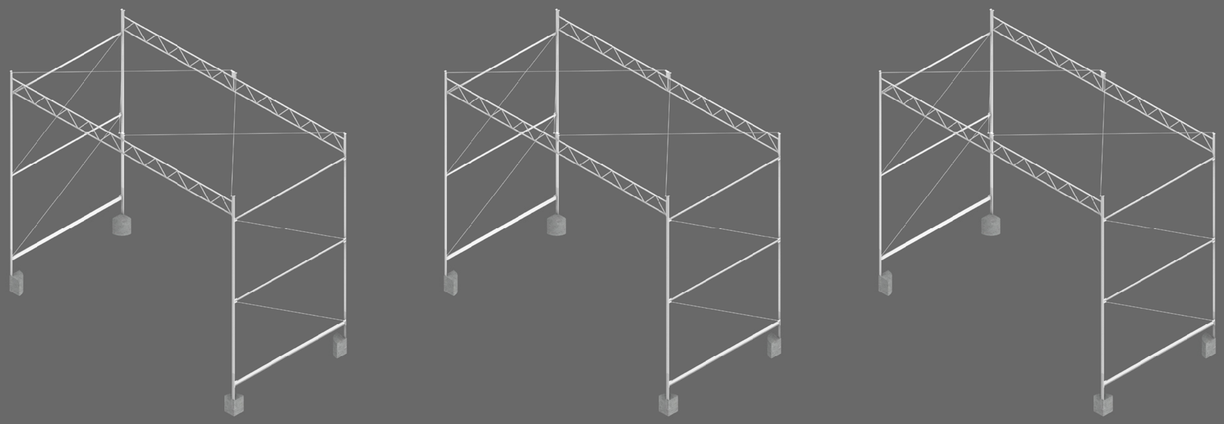
In the icons in p3 module c2 principles, the isometrics of modules do not depict the ventilation windows. Instead, they focus on illustrating the distinction between full-panes and half-panes. However, it is important to note that the ventilation windows within the modules follow the structure of the deck.



bay-link corner *trellis-link corner* *endwall*



half-pane sidewall *transition sidewall* *full-pane sidewall*



half-pane midfield *transition midfield* *full-pane midfield*

figure 22: gables of the nine of the module types (own, 2023)

For instance, on a half-pane deck, the deck rods extend below the windows, but only at half the distance compared to the deck rods located beneath the windows on a full-pane deck. This design ensures alignment between the deck structure and the placement of ventilation windows within the modules.However, due to the difference in wind load between the deck and the gable, the glazing on the deck is divided into four full-panes/eight half-panes, rather than the six full-panes/twelve half-panes used for a sidewall gable. This means that the glazing on the deck is not aligned with each sidewall gable pane. The icons in the p3 module c2 principles may give the impression that the half-pane and full-pane sizes are the same for the deck and gables, but this is done to simplify the understanding of greenhouse construction principles only.

When it comes to opening the ventilation windows, a push rod is used, which is driven by a motor. The push rod is mounted on a trellis, which serves as the boundary for the modules. It connects to the center of the aluminium window frame. In the case of the MightyVine phase 3 case study, three-pane windows are used. This means that a window is as wide as three full-panes or six half-panes. To ensure that the center of a window is always positioned above a trellis when there is an odd number of panes in a window, the panes on the deck are offset by half a full-pane (or one half-pane). This offset can be seen clearly in Figure 23, which depicts the isometric view of a full-pane midfield deck, where the panes are split in half at the boundary of the midfield module.

endwall and sidewall deck

In the case of the endwall deck, all endwall modules have the same components as they are all glazed with half-panes and feature identical ventilation windows. However, because the endwall gable has to be seamlessly connected to them, these modules are slightly wider compared to the sidewall modules. As a result, the deck of the endwall modules is slightly wider as well. To fill the additional space between a regular window and the gable in the endwall modules, a fitting window is used. This fitting window is a very narrow window that occupies the extra space. Alternatively, some greenhouses may use an aluminium cover profile to fill this space, but this comes at the expense of reducing the admission of daylight.

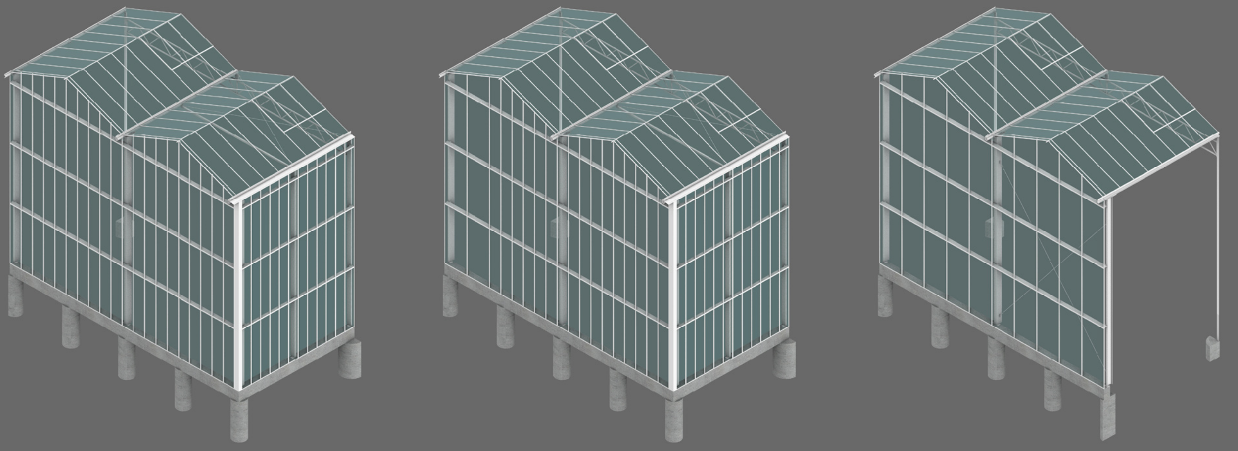
In sidewall decks, the main difference can be observed in the second peak from the sidewall. Here, there are three options for the configuration: eight half-panes, five half-panes and one-and-a-half full pane, or four full panes. The choice depends on the modules that will be adjacent to these sidewall modules. In a transition sidewall module, the configuration consists of five half-panes (equivalent to two-and-a-half full panes). This is because the full-pane needs to be shifted half a pane to ensure that the center of the three-pane window aligns with the trellis where the push rod is mounted. By maintaining this alignment, the window can be pushed open perpendicularly, instead of under an angle, which is more practical.

midfield deck

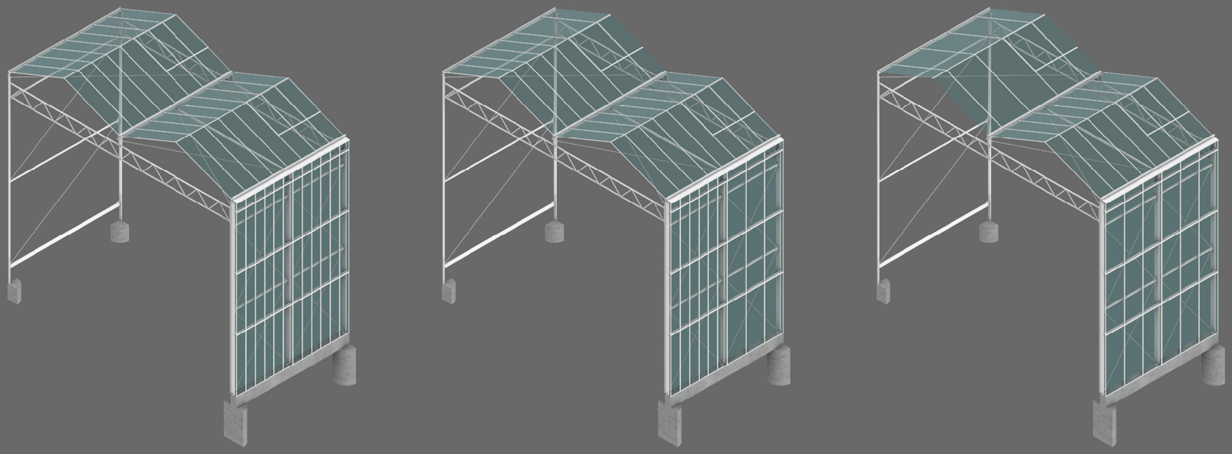
Midfield decks show the most differences among the options, because here both peaks are half-pane, transition, or full-pane, unlike the sidewall modules in which only one peak differs. Again, the rule of thumb of shifted windows for alignment with the trellis applies, so all glazing is shifted half a pane.

deck reuse

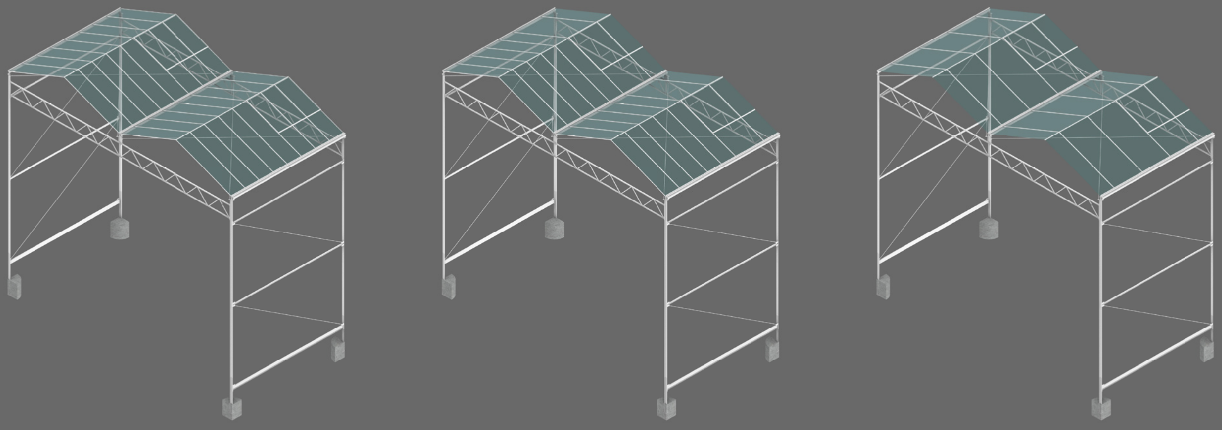
Again, aluminium profiles can be reused but the rubbers and PVC strips need to be replaced as they easily deform onehrer during disassembly of the greenhouse due to rigidity and brittleness.



bay-link corner *trellis-link corner* *endwall*



half-pane sidewall *transition sidewall* *full-pane sidewall*



half-pane midfield *transition midfield* *full-pane midfield*

figure 23: decks of the nine of the module types (own, 2023)

components per module

To calculate the carbon footprint of modules in p6 carbon c1 modules, an overview of the components in each one is essential; that list is compiled in *table 1*. Like the isometrics, components on the boundary of modules are split. **Important:** this table only provides the data for concrete (totoal volume per component, in m^3), steel (total number per component, in #), and glass (total area per gable/deck, in m^2). To calculate the volume of aluminium/rubber/PVC gable and deck components, a 3D-model is made of all modules. To calculate the carbon footprint of those components, the combined volume of components *per* material *per* module is calculated. A similar approach is used to convert the data of concrete, steel, and glass number to a volume. The exact volumes of all components, including the grouped gable and deck components, are included in the table in appendix 7a-7c, which is also the source of calculations in p6 carbon c1 modules.

table 1: components per module (own, 2023)

Group	Component	Material	Dimensions	N/R	bay-link corner	trellis-link corner	endwall	half-pane sidewall	transition sidewal	full-pane sidewall	half-pane deck	transition deck	full-pane deck
[-]	[#]			[-]	$[m^3]$	$[m^3]$	$[m^3]$	$[m^3]$	$[m^3]$	$[m^3]$	$[m^3]$	$[m^3]$	$[m^3]$
Foundation	Endwall pile	Concrete	d = 500 mm, h = 1,450 mm	N	1.28	1.28	1.14	-	-	-	-	-	-
	Sidewall pile	Concrete	d = 762 mm, h = 1,250 mm	N	0.29	0.29	-	0.57	0.57	0.57	-	-	-
	Gable beam	Concrete	w = 240 mm, h = 400 mm	N	1.30	1.30	0.86	0.43	0.43	0.43	-	-	-
	Midfield pile	Concrete	d = 762 mm, h = 550 mm	N	0.06	0.06	0.13	0.13	0.13	0.13	0.25	0.25	0.25
	Floor	Concrete	h = 150 mm	N	5.87	5.87	5.91	6.03	6.03	6.03	6.07	6.07	6.07
					[#]	[#]	[#]	[#]	[#]	[#]	[#]	[#]	[#]
Foundation	Column	Steel	l = 1,250 mm, RHS = 160x60x3	N	0.25	0.25	0.50	0.50	0.50	0.50	1.00	1.00	1.00
	Foot plate	Steel	l = 160, w = 60 mm, h = 3 mm	N	0.25	0.25	0.50	0.50	0.50	0.50	1.00	1.00	1.00
Structure	Endwall column	Steel	l = 6,722 mm, RHS = 200x120x5	R	2.50	2.50	2.00	-	-	-	-	-	-
	Sidewall column	Steel	l = 6,722 mm, RHS = 160x80x4	R	1.50	1.50	-	2.00	2.00	2.00	-	-	-
	Midfield column	Steel	l = 6,373 mm, RHS = 160x60x4	R	0.25	0.25	0.50	0.50	0.50	0.50	1.00	1.00	1.00
	Foot plate	Steel	l = 250, w = 100 mm, h = 6 mm	R	4.00	4.00	2.00	2.00	2.00	2.00	-	-	-
	Endwall purlin	Steel	l = 9,000 mm, U = 120x40x2.5	R	3.00	3.00	3.00	-	-	-	-	-	-
	Sidewall purlin	Steel	l = 4,500 mm, U = 80x40x2.5	R	3.00	3.00	-	3.00	3.00	3.00	-	-	-
	Purlin corner	Steel	l = 40 mm, L = 40x40x4	R	15.00	15.00	12.00	6.00	6.00	6.00	-	-	-
	Purlin corner	Steel	l = 40 mm, L = 90x40x5	R	3.00	3.00	-	-	-	-	-	-	-
	Trellis girder	Steel	l = 8,816 mm, RHS = 60x30x2.5	R	1.00	1.00	1.00	2.00	2.00	2.00	2	2	2
	Trellis diagonal	Steel	l = 594 mm, RHS = 25x25x2	R	10.00	10.00	10.00	20.00	20.00	20.00	20.00	20.00	20.00
	Trellis mid vertical	Steel	l = 440 mm, RHS = 50x25x2	R	0.50	0.50	0.50	1.00	1.00	1.00	1.00	1.00	1.00
	Trellis end plate	Steel	l = 60 mm, w = 12 mm, h = 576 mm	R	1.00	1.00	1.00	2.00	2.00	2.00	2.00	2.00	2.00
	Mid trellis post	Steel	l = 202 mm, RHS = 120x60x3	R	0.50	0.50	0.50	1.00	1.00	1.00	1.00	1.00	1.00
	Mid trellis post foot plate	Steel	l = 210 mm, w = 60 mm, h = 6 mm	R	0.50	0.50	0.50	1.00	1.00	1.00	1.00	1.00	1.00
	Gutter plate	Steel	l = 430 mm, w = 140 mm, h = 5 mm	R	2.50	2.50	2.00	-	-	-	-	-	-
	Gutter plate	Steel	l = 130 mm, w = 100 mm, h = 5 mm	R	2.25	2.25	1.00	3.50	3.50	3.50	2.00	2.00	2.00
	Endwall bracing brace	Steel	l = 2,170 mm, d = 10 mm	R	-	-	2.00	-	-	-	-	-	-
	Endwall bracing plate	Steel	l = 50 mm, w = 6 mm, h = 80 mm.	R	-	-	4.00	-	-	-	-	-	-
	Sidewall bracing brace	Steel	l = 3,330 mm, d = 10mm	R	-	-	-	8.00	8.00	8.00	-	-	-
	Sidewall bracing plate	Steel	l = 50 mm, w = 6 mm, h = 80 mm.	R	-	-	-	16.00	16.00	16.00	-	-	-
	Sidewall bracing crossbeam	Steel	l = 2,150 mm, RHS = 50x50x2	R	-	-	-	4.00	4.00	4.00	-	-	-
	Sidewall bracing end plate	Steel	l = 50 mm, w = 10 mm, h = 150 mm	R	-	-	-	8.00	8.00	8.00	-	-	-
	Mifield bracing brace	Steel	l = 5,000 mm, d = 10 mm	R	-	-	-	2.00	2.00	2.00	4.00	4.00	4.00
	Midfield bracing plate	Steel	l = 50 mm, w = 6 mm, h = 80 mm.	R	-	-	-	4.00	4.00	4.00	8.00	8.00	8.00
	Midfield bracing crossbeam	Steel	l = 4,416 mm, RHS = 120x60x3	R	-	-	-	0.50	0.50	0.50	1.00	1.00	1.00
	Midfield bracing crossbeam	Steel	l = 4,420 mm, RHS = 50x50x2	R	-	-	-	1.00	1.00	1.00	2.00	2.00	2.00
	Midfield bracing end plate	Steel	l = 60 mm, w = 12 mm, h = 220 mm	R	-	-	-	1.00	1.00	1.00	2.00	2.00	2.00
	Midfield bracing end plate	Steel	l = 50 mm, w = 10 mm, h = 150 mm	R	-	-	-	2.00	2.00	2.00	4.00	4.00	4.00
	First gutter row bracing brace	Steel	l = 4,600 mm, d = 10 mm	R	2.00	2.00	-	2.00	2.00	2.00	-	-	-
	First gutter row support plate	Steel	l = 50 mm, w = 6 mm, h = 80 mm.	R	3.00	3.00	-	3.00	3.00	3.00	-	-	-
	First gutter row support beam	Steel	l = 4,453, RHS = 50x50x2	R	1.00	1.00	-	1.00	1.00	1.00	-	-	-
	Gutter console	Aluminium	*extruded profile*	R	2.00	2.00		2.00	2.00	2.00			
	Gutter console plate	Aluminium	l = 50 mm, w = 5 mm, h = 100 mm	R	1.00	1.00	-	1.00	1.00	1.00	-	-	-
	Deck bracing brace	Steel	l = 6,030 mm, d = 8 mm	R	-	-	-	2.00	2.00	2.00	4.00	4.00	4.00
	Deck bracing plate	Steel	l = 50 mm, w = 6 mm, h = 80 mm.	R	-	-		4.00	4.00	4.00	8.00	8.00	8.00
					$[m^2]$	$[m^2]$	$[m^2]$	$[m^2]$	$[m^2]$	$[m^2]$	$[m^2]$	$[m^2]$	$[m^2]$
Gable	Gable panes	Glass	d = 4 mm	R	89.9	90.2	63.1	28.4	28.8	29.2	-	-	-
Deck	Deck panes	Glass	d = 4 mm	R	42.1	42.1	42.1	41.2	41.4	41.6	42.0	41.5	41.2

p3

module

The research in each part is conducted to answer one or more sub-research questions, which will ultimately help answer the main research question. These sub research questions are answered by means of a certain product, identified in p1 intro c3 research. The results are discussed here.

In p3 module two sub research questions have been answered, the second and third one. The questions and the approach to finding an answer to it were:

2. Regarding the aspect ".... reused greenhouse components": *"What components become available when a greenhouse is demolished?"*. It is answered in p3 module by means of an overview of a case study greenhouse's components that can be reclaimed upon demolition.

This question is answered in c1 case study. The answer is: the list of components that can be retrieved whe na greenhouse is demolished consists of all steel columns, trellises, bracing, gutter supports, and purlins; all aluminium gutters, ridges, and rods; and all deck and gable panes. The complete list of components can be retrieved in appendix 4.

3. Regarding the aspect "urban modular farming": *"How can modules be built from reused greenhouse components and what conditions should modules meet?"*. It is answered in p3 module by means of an illustrated overview of the principles of greenhouse construction to which structures must conform **and** an overview of the different modules to design based on those greenhouse construction principles **and** a design for each of the different modules in 3D.

The first part of this question (*"How can modules be built from reused greenhouse components..."*) is answered in c3 design, the second part (*"... and what conditions should modules meet?"*) in c2 principles. To provide an answer to the first part, the reader is referred to the build-up renders in c3 design. To provide a concise answer to the second part, a summary of greenhouse construction principles is given below, addressing both the use of a grid and half-panes to absorb high wind loads near corners:

To construct a hybrid urban vertical farm module, it is important to consider two key factors. First, the module should be built on a grid that matches or is smaller than the original greenhouse's grid, from which the components are being reused. This ensures that the components fit together within the grid or can be adjusted to fit within a smaller grid if necessary. Second, for modules using components from MightyVine phase 3, it is crucial to have at least one-and-a-half peaks of half-panes in each sidewall and one-and-a-half bays of half-panes in each endwall. This arrangement helps reduce the wind load on each glass pane and improves load absorption. The implementation of half-panes also extends to the first one-and-a-half bays behind the endwall gable and the first peak next to the sidewall gable. To ensure that at least one-and-a-half peaks or bays in each corner of the sidewalls and endwalls are covered with half-panes, nine modules need to be designed. These nine modules have been extensively discussed and illustrated in c2 principles, including their appearance in various module configurations.

part four

system

p4

system

in this part

P4 sytem presents the design of the innovative growing system. However, before any design can be made there is a need for knowledge about the features that the design have. Therefore, c1 crop needs addresses what resources crops need to grow well. Then, in order not to repeat mistakes already made in existing vertical farms and to discover what strong, desirable features could be for the growing system to be designed, an analysis of existing vertical farming typologies is made in c2 typologies. The knowledge about crop needs and the desired features are then combined in the design of an innovative growing system: that is presented and explained in c3 design. In conclusion, the third chapter addresses the structural quality of the growing system; it assessed whether the structure is strong enough to support the crops.

To gain insight into practical approaches to provide crops in vertical farming systems with the resources they require, a visit was made to Artechno, De Lier, the Netherlands. This company builds fully automated vertical farming systems that are sold all over the world. The persons spoken to are commercial manager Rudy van den Berg, company CEO Marco van der Velden. This visit is refered to as *(van den Berg, R. & van der Velden, M. [Artechno], personal communication, January 09, 2023)*.

To gain insight into the crop density that can be achieven in a greenhouse that uses a two-layer growing system, a visit was made to Sion, De Lier, the Netherlands. This company is the largest orchid breeder of Europe. The person spoken to is ICT & Data specialist Emiel Moor. The visit is refered to as *(Moor, E. [Sion], personal communication, February 02, 2023)*.

c1 **crops needs**

c2 **typologies**

c3 **design**

in this chapter

The design of a growing system is about the construction and how it works mechanically. It does not address what type of radiation comes through the deck, what concentration of CO_2 *is provided, what pH value the irrigation water has, and what nutrients should be dissolved in it. This is because this research focuses on the cultivation area, and* ***not*** *on the technical room attached to a module configuration where the climate and irrigation of the greenhouse is controlled. However, in order to be knowledgeable about what crops need, a literature review of light and other requirements such as* CO_2*, water, nutrients, and pollination is conducted. That knowledge has influenced choices in the design of the growing system.*

photosynthesis

Life on Earth depends on photosynthesis, carried out by plants, algae, and some bacteria. They capture energy from sunlight, carbon dioxide from air, and water from soil, to produce chemical energy in the form of glucose. Water is oxidised (losing electrons), carbon dioxide is reduced (gaining electrons), this turns water into oxygen and carbon dioxide into glucose. For plants, oxygen is a by-product. Oxygen is released back into the air and glucose molecules are stored within the plant. The chemical reaction is:

$$6H_2O + 6CO_2 + sunlight \rightarrow C_6H_{12}O_6 + 6O_2$$

Herbivores obtain energy (sugar) stored in plants by eating them, then they are eaten by carnivores, with some smaller carnivores being eaten by larger ones, and so on. Each higher trophic level obtains energy to live off of, by consuming energy in plants/prey animals (Reece et al., 2017). After their death, consumers (herbivores and carnivores) decompose, and the nutrients stored in them return to the soil, where producers (plants) absorb them to support their lives and continue the process of photosynthesis. Now that it is clear why water, light, and air are required, a description of these and their supply can be given in the following sections, as well as other required nutrients/processes for plant growth.

photoperiodism

Plants require (day)light to grow, some crops are long-day plants, some are neutral-day plants, and others are short-day plants. Depending on the crop, it is beneficial to lengthen or shorten the day length, i.e., the amount of hours plants receive light. Shortening/lengthening the natural light timespan changes the photoperiod: the duration of light availability during a timespan, often per twenty-four hours. This inherently changes photoperiodism: the response of plants to the relative length of light and dark periods (Boyle, 2017). Photoperiodism also occurs during twilight, which is the time before sunrise and after sunrise when the sun is 6° below the horizon. During twilight, the light intensity is high enough to induce photoperiodism. Moonlight, either new moon or full moon, is not intense enough to achieve that. Additionally, shading from surrounding buildings can reduce light intensity, both during twilight and the rest of the day, and prevent the occurrence of photoperiodism (Boyle, 2017).

Photoperiodism can be lengthened or shortened. Lengthening is achieved by extending a short day (SD) to a long day (LD) with artificial lighting system. Shortening can be achieved by closing dark/opaque horizontal (climate) screens and vertical screens to reduce or block intruding daylight from the greenhouse. Common screen materials are black sateen cloth (jet black woven cloth), polyolefin sheeting (woven, tear-resistant, and waterproof), or black plastic (not tear-resistant, requires maintenance).

sunlight

Using sunlight is superior to the use of assimilation lighting. So far, the intensity of global radiation is still higher than any artificial light product on the market can deliver. Of course, plants do not use all of the wavelengths present in sunlight, after all, their absorption and action spectrum does not depend on the light source, but as sunlight is free it remains a superior source of energy compared to all (wavelength specific) artificial lighting. Therefore, the key is to let in, diffuse and utilize as much sunlight as possible.

artificial light

When daylight is not available in amount considered sufficient for commercial crop growing, artificial lighting can be used to provide crops with the amount of light they need for proper development. Artificial lighting is integrated in modern agriculture to provide crops with enough light to succeed in the light-dependent stage of photosynthesis, in which chlorophyll absorbs energy from light waves and converts it into energy. Light to feed the plant with energy is called *assimilation light*, derived from *assimilation*; a biochemical process in which an organic compound (photosynthesis: glucose) is built up from simpler organic compounds or from inorganic substances, particularly carbon dioxide and water. This requires energy, which is provided by the assimilation lights. On average, the illuminance of assimilation light is 8,000 lux (105 µmol/m^{2}s) (Kwekenmetled, n.d.).

Previously, high-pressure mercury lamps used to be commonly used, they were later replaced by high-pressure sodium lamps (SON-T). Since 2007 LED is standard as it has numerous advantages like low operating temperatures, low light pollution, no current spikes when switched on, almost no blind current, customization, and a long service life (50,000 hours, compared to 10,000 hours for high-pressure sodium lamps). Despite advantages of LED over SON-T lamps, hybrid installations of both are increasingly common for a variety of crops. The fixtures of the hybrid sections are installed in a checkerboard pattern over crops. SON-T high-pressure assimilation lamps have a broad light spectrum, allowing them to be used for illuminating different types of crops. LED has the added advantage of delivering remarkably more output, but with less power. Advantages of hybrid lighting are (Voshol Warmte-Elektrotechniek, n.d.) an increase light level, more light without additional heat, a customizable light spectrum, and energy-savings and an increase service life (due to LED).

Hybrid lighting is advantageous for any crop (tomato, lettuce, herbs, etc.). A customized regime can be devised for each crop. This allows optimal use of the light and heat offered. Because of this tuning, crops grow optimally in sunny and dark periods. If the light level needs to be increased, the available power of the installation in the greenhouse is a common limitation. In these situations, increasing the light level is only possible when the SON-T fixtures are replaced by (more energy efficient) LED grow light.

color

The visible spectrum consists of wavelengths between 380-750 nanometres, from red, through green, to blue light. Crops need each for different reasons, and they have varying degrees of sensitivity to different wavelengths. Depending on the cellular and molecular composition of the leaves, the absorption and action spectrum differ. The absorption spectrum determines which wavelengths are being absorbed by the plant. A study (Gorton, 2010) on twenty-two common crops shows that wavelengths between 500-600 nanometres (green) are mostly outside this range, these are reflected, causing plants to be perceived as green.

The action spectrum is the range of wavelengths useful for photosynthesis, these are primarily red (600-700 nanometres) and blue (400-500 nanometres), green is right in between. Good assimilation lamps emit the absorption and action spectrum of the crop they illuminate; modern LED assimilation lamps can emit targeted red and blue light; together, these produce the characteristic **pink color** of assimilation lighting in greenhouses . This keeps the ratio of energy consumption to photosynthesis initiation favourable (Gorton, 2010). For flowering, infrared light, emitted in the form of heat, is preferred. Incandescent bulbs can work for this purpose, but as they also produce light, they are not energy efficient in fulfilling that purpose.

co$_2$

Greenhouses require active supply of carbon dioxide to compensate losses of CO_2 back into the outdoor through ventilation windows. The optimal concentration of CO_2 in the indoor climate is 800 parts per million (ppm) (Graamans et al., 2018). In chapter 99, part 99, three different ways of supplying CO_2 are discussed: 1) combustion of natural gas, 2) pure liquid CO_2 supply, and 3) fossil fuel combustion. These were explained in p2 reuse c1 components.

water

Next to soil and air, water is the main supply stream of supplies to plants. In addition to H2O molecules (photosynthesis), nutrients can dissolve in it. Water must be clean enough to allow uptake of nutrients. Three factors determine the quality of horticulture irrigation water: pH, alkalinity, and soluble salts. The latter is discussed in the next subsection. pH is a measure of the concentration of hydrogen ions (H^+) in water or other liquids. The pH value should remain between 5-7 and can be tested by means of a litmus test or a more advanced digital pH measuring device. Water with a pH below five is termed ‘acidic’, whilst water with a pH above seven is termed ‘basic’ (University of Massachusetts Amherst, n.d.).

Alkalinity defines water’s ability to make acids less acidic (neutralize water’s acidity) and is dependent on the amount of calcium carbonate dissolved in the water. Thus, it can be measured by testing the level of bicarbonates, carbonates, and hydroxides. These dissolve in water when it erodes its aquifers materials, like limestone and dolomite. Alkalinity is expressed as ‘ppm of calcium carbonate ($CaCo_3$)’. Alkalinity of 0-100 is acceptable, but 30-60 is considered an optimum for common horticulture crops. Irrigation water should be tested for both pH and alkalinity, as a pH test is not an indicator of alkalinity. Water with high alkalinity (many bicarbonates or carbonates) often has a pH of seven or more, but water with high pH does not always have high alkalinity. Testing if irrigation water has high alkalinity is of utmost importance, because it is a high alkalinity, not a high pH value, that significantly affects growth medium fertility and plant nutrition (University of Massachusetts Amherst, n.d.). Irrigating with a pH above seven is acceptable as long as the alkalinity does not exceed the acceptable range. However, irrigating with a both a high pH and a high alkalinity is harmful to the receiving crops.

contamination

The presence of soluble salts is measured by the electrical conductivity of the solution, expressed in millisiemens/centimetre (mS/cm). Untreated water should be between 0.1-1.5 mS/cm, but a conductivity < 1.0 mS/cm is recommended for plugs. Fertilized water contains more soluble salts due to the dissolved substances in the water. The optimal conductivity range is 1.5-2.5 mS/cm, to not damage plants as excess soluble salts hinder root function, leading to reduced water absorption and nutrient deficiency.

Irrigation systems have filters to capture and remove suspended solids, to prevent them from clogging pipes, valves, nozzles, and emitters further along in the irrigation system, preventing irrigation cut-offs. Crops have an optimal range for the concentration of a variety of naturally occurring minerals in water. At lower concentrations, extra substance should be added (University of Massachusetts Amherst, n.d.).

Optimal concentrations are; calcium: 40-100 ppm; magnesium: 30-50 ppm; natrium: < 50 ppm; chlorin: < 140 ppm; potassium: if the concentration is > a few ppm, the water is likely to be eutrophicated; phosphate: if the concentration is > a few ppm, the water is likely to be eutrophicated; sulphate: if the concentration < 50 ppm, more should be added (essential plant nutrient); ammonium: if the concentration is > 5 ppm, the water is likely contaminated with fertilizer; and nitrate: if the concentration is > 5 ppm, the water is likely contaminated with fertilizer.

nutrients

Besides water, carbon dioxide, and light, plants require more elements to remain healthy and support their bodily processes. In total, plants require sixteen nutrients, in descending order of amount these are:

- Photosynthesis compounds: carbon, hydrogen, and oxygen;
- Primary macronutrients: nitrogen, phosphorous, and potassium;
- Secondary macronutrients: calcium, magnesium, and sulphur;
- Micronutrients: zinc, manganese, copper, iron, boron, molybdenum, and chlorine.

Noteworthy, only three elements are supplied through air and water (carbon, hydrogen, and oxygen), the other thirteen are to be supplied through irrigation. It is important that water in which nutrients are dissolved has an acceptable alkalinity and pH level. If not, the solution can become too acid for the roots to absorb nutrients which makes them miss out on elements they need, resulting in low productivity and crop yield, ultimately lowering commercial profit (My Agriculture Information Bank, 2018).

In both nature, soil-based horticulture, and nutrient rich media based hydroponic agriculture, bacteria live in plant roots in a symbiotic manner. They fix nitrogen in ammonia (NH_3) and ammonium (NH_4^-). Next, nitrifying bacteria transform that to nitrite (NO_2^-) and nitrate (NO_3^-), which are easy to assimilate by plants. When animals or plants die, the nitrogen fixed in them is returned to the soil as ammonia, in a process called ammonification, ready to be taken up by living plants again. Plants prefer nitrogen stored in ammonia (NH_3) over nitrite (NO_2^-) and nitrate (NO_3^-), as ammonia is easier to transform. Denitrifying bacteria can transform nitrite and nitrate back into atmospheric nitrogen gas. When fertilizer containing nitrogen are overused, it can outwash into natural water bodies, where algae growth will blossom, blocking sunlight and preventing underwater flora from photosynthesis. When algae die, their decomposing process uses up almost all oxygen in water, killing underwater fauna. To conclude, irrigation with fertilizer is a meticulous task. Concentrations should not be too high, water should have a good pH and alkalinity, and excess fertilizer must not be used when outwash is possible.

pollination

For plants to survive it is essential for them to reproduce, for plants this happens through pollination; the act of transferring pollen grains from the male anther of a flower to the female stigma of a flower.

In nature, wind, birds, bees, and bats take care this. However, in closed greenhouses these natural caretakers are not available. There are some techniques for horticulture (Produce Grower, 2017):

- Bumblebees: can be bought per colony, they pollinate plants in the natural way, but there is a risk that not all plants are pollinated and/or that crops do not develop simultaneously;
- Manual labour: pollen is either transferred with a brush (for small-scale practices) or vibrated loose into clouds by tapping the plant with a stick, hoping it will reach the female stigma;
- Polybee: microdrones bring male pollen grains from one flower to the female stigma of another flower, the technique is still new, but allows for relative simultaneous pollination;
- Pollination spray: applying auxin-based rooting hormones to promote flower development. Often, plugs are dipped in this fluid to stimulate future pollen development (unliked by farmers).

It is important to maintain a proper balance between vegetative growth (production of leaves and other green bits) and generative or reproductive growth (flowers and fruits). If balance cannot be maintained, most of the plant's energy is used for vegetative growth, and not the desired fruits that are of commercial value (saleable product). Moreover, if little flowers/fruits are produced, less pollen/seed are available to pollinate/grow the next cycle of crops (Produce Grower, 2017). When farming leafy greens (herbs, lettuce, etc.) pollination is superfluous, since no fruits are harvested from these cultivars, but the complete crop is harvested for commercial purposes.

The research conducted in this chapter has been incorporated in the design of a hybrid urban vertical farm. Now, at its conclusion, references are made to the chapters in which the features identified as important in this chapter have been incorporated into the design.

- In the designed growing system, containers of crops rotate toward daylight, but in doing so they do not receive enough daylight (34% annually) to meet their full light requirements. Therefore, the system is equipped with nine artificial lights to supplement the deficit (p4 system c2 design);
- Also applicable to artificial light; in winter (December) crops can meet only 17% of their light needs with daylight, because the sun shines and is less intense and less long above the horizon. Allowing artificial light to shine more intensely during those days extends the photoperiod (p5 optimize c1 light);
- Since crops need more red and blue light and less green light, an artificial light that emits in those spectra was chosen to make the best use of the energy consumed by the lights (p4 system c2 design);
- Although the design of a technical room is not part of this thesis, recommendations have been made to provide the resources required to meet crop needs other than daylight in a renewable manner, such as water from sewage treatment plants, CO_2 from industrial byproducts, and nutrients from biowaste/treated runoff water (p7 integration c2 resources).

in this chapter

To improve something, one must know what the current state of affairs is. In order to be able to design an improved (vertical) growing system in the next chapter, in this chapter eight existing vertical cultivation typologies are studied. Each is rated according to its floor space index and a set of icons. At the end of this chapter, it is concluded which features of existing typologies a new growing system should combine.

approach

This chapter presents a description and visual representation of nine different vertical farming typologies. Each typology is accompanied by a drawing showcasing how it would fit in a module; occupying a volume of 4,500 mm (one peak) by 4,500 mm (one bay) by 6,000 mm (free space under trellis). It's worth noting that this size is **half the footprint** of a single module measuring 9,000 mm (one trellis) by 4,500 mm (one bay). The remaining half is allocated for technical space. When modules are linked, the need to reserve half of *every* module for technical rooms is eliminated, allowing (way) more than half of the space to be used for cultivation. However, to evaluate the efficiency of the typologies in the smallest possible configuration (one module), drawings and calculations are based on a volume of 4,500 by 4,500 by 6,000 mm.

From the drawings, the floor space index (FSI) of each typology is determined. The FSI is calculated by dividing the total cultivation surface by the occupied footprint of the typology. The footprint, known as the ground space index (GSI), remains consistent for all typologies, measuring 4,500 by 4,500 mm, or 20.25 m^2. The FSI of each typology is represented as a percentage relative to the GSI, which is calibrated at 100%. This allows for easy identification of the most space-efficient typology based on the highest FSI percentage. Together with the FSI calculations, the chapter summarizes the general characteristics in terms of durability, ease of use, etc. of each typology through a series of positive/negative icons. The conclusion aggregates all the analyses and ranks the typologies based on their FSI and number of positive icons. Furthermore, the chapter explores which typologies can be used effectively without the need for supporting machinery and provides recommendations for creating sustainable combinations of typologies. These insights serve as valuable inputs for designing a hybrid urban vertical farming system.

parameters

Layer distance: between crops and LED lighting, a space of 450 mm is kept free. This is a normal distance to use high-intensity artificial light to adequately illuminate crops without risk of burning the crops (van den Berg, R. & van der Velden, M. [Artechno], personal communication, January 09, 2023).

Crop density: to calculate the number of crops that can be grown on the footprint of half a module (20.25 m^2) and on the surfaces of the growing systems that are drawn, one basic crop, lettuce, was chosen. Lettuce seeds require a spacing of 20 cm in all directions; thus, a crop of lettuce requires 0.20 meter by 0.20 meter, or 0.04 m^2. Thus, on the footprint of half a module, 20.25 m^2 / 0.04 m^2 = 506 crops of lettuce can be grown.

Aerial platform: some typologies are rather high, which means that an employee cannot reach crops that grow on the highest level without assistance of an aerial platform. Obviously, some space must be reserved around typologies to allow them to drive around. It is assumed that a (small) aerial platform takes up 1.5 m^2, equal to the dimensions of the smallest aerial platform offered by horticultural company Berg Hortimotive that can reach up to 4.2 meter high (Berg Hortimotives, n.d.).

remark

This approach takes a fairly rough look at how each of the typologies would fit into half of a hybrid urban vertical farming module. There are indefinite ways to accommodate each of the typologies in a module, and not all of them require half a module of space for technology and storage. Besides, there are bound to be more space-efficient layouts than the ones drawn. However, this chapter is written as an insight into the pros and cons of each typology, **not** as a comprehensive design and optimization exercise.

icons

The evaluation emphasizes the FSI. However, there are more features that are important, therefor icons are developed (*figure 24*) to categorize typologies. Some indicate sustainability; others distinguish movements and structural features. Icons are not necessarily right or wrong; but some do contribute to higher durability (e.g., naturally lit), better repairability (e.g., low-tech), a longer service life (e.g., manual), the advantage of not needing an aerial platform (e.g., accessible), and the advantage of not needing an additional supporting structure (e.g., self-supporting). Icons that represent desired characteristics are colored green, their counterparts red. (Dis)advantages that cannot be captured in icons are explained textually. If a typology with a high FSI does not score well in terms of positive icons, recommendations will be made to improve it in the design of a new growing system. **Important**: the score of positive icons is secondary to the FSI, so space-efficient typologies are not disregarded too fast; as ultimately, that would be to the detriment of the efficiency of the growing system that will be designed.

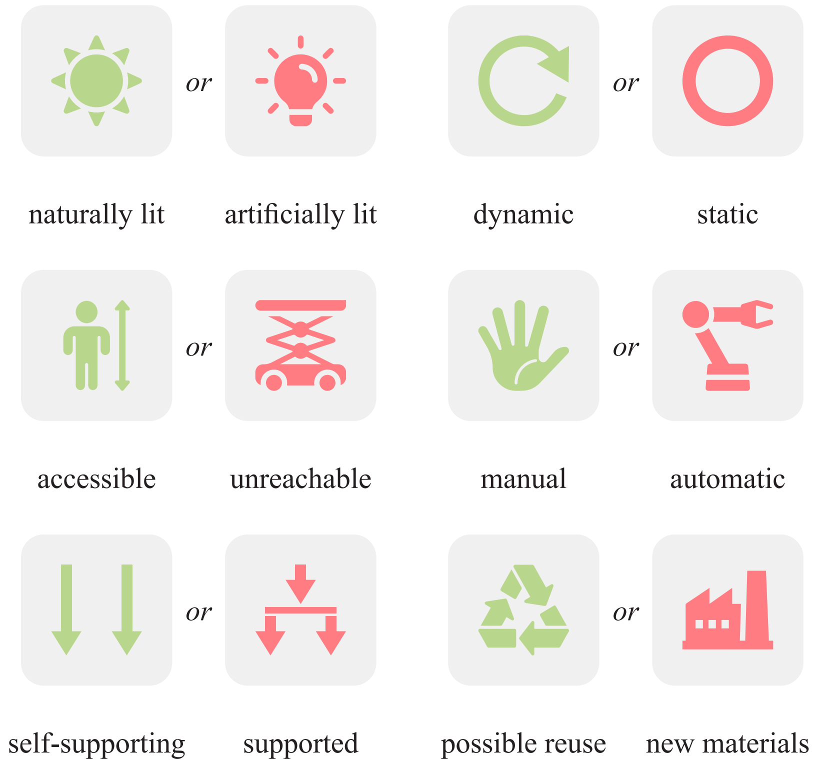


figure 24: sustainability icons

one-layer

Ornamental plant growers, as well as cress grower Koppert Cress, use one-layer container systems. Here, plants are put together in trays on a container by potting date, stage of maturity, and/or by color. Each container has a barcode that is read by sensors and displayed in horticultural software. Growers know exactly where each crop is and can move them to work stations with transport belts, roller conveyors, push-up systems, or wheeled robots. Containers are seamlessly arranged, with one position left vacant per lane to facilitate movement between lanes. Moreover, walkways are incorporated every two lanes, allowing employees to efficiently work with the crops in the greenhouse.

figure 25: one-layer growing system (Koppert Kress, 2021)

Along endwalls, there is space for robots to transfer containers between lanes. Importantly, workspace is situated in an adjoining warehouse, so it doesn't take up greenhouse space. It is conservatively estimated that 95% of the greenhouse's land area is effectively utilized by containers, specifically designated for crop cultivation. This proportion is visually depicted in *graph 3*. **Graph explanation:** the orange bar indicates how the FSI of the discussed growing system compares to the GSI of the footprint of half a module. Thus, the bench mark FSI is 100%, visualised as a white line in the graph. If the orange bar ends before the bench mark of 100%, then (in terms of the amount of crops that can be grown per m^2 footprint) it *is not* beneficial to use the growing system compared to just using the land as if it were open-field cultivation. If it is above the bench mark of 100% , it *is* beneficial to apply the growing system, so more crops per m^2 can be grown.

graph 3: one-layer growing system FSI (own, 2023)

two-layer

Sion Orchids, Europe’s largest orchid growers from De Lier, The Netherlands, operates a semi two-layer system. In three of their greenhouses, young plants and half-grown plants are cultivated with a one-layer container system. However, older plants need to mature; they need to develop longer branches and mature buds. These do not need the tropical greenhouse climate, but rather benefit from a cooler environment. These are therefore moved by a lifting robot to container lanes above the workspaces in a cooler storage area. Half-grown plants to be transported abroad are also stored there to pause growth. This way, empty space is conveniently used to give plants a place that would otherwise take away cultivation area.

figure 26: two-layer growing system (own, 2023)

There is no straightforward calculation to determine how much higher the FSI will be than the GSI when a (semi) two-layer system is used in greenhouses and warehouses. This is because it depends on the size of the warehouse, not the greenhouse. To still give an indication for this typology, which is essentially the simplest vertical farm system one can imagine, the situation at Sion is specifically calculated. In their growing system, they have a total of 5,758 containers in a one-layer system. As the one-layer system FSI calculation showed, these (one-layer) containers result in a FSI of 95%. In addition, Sion Orchids has 890 containers on lanes above workspace in warehouses (Moor, E. [Sion], personal communication, February 02, 2023). If 5,758 containers equal a FSI of 95%, then 6,648 containers (5,758 + 890 containers) ratiowise equals a FSI of 106%. This ratio is shown in *graph 4*.

graph 4: two-layer growing system FSI (own, 2023)

standing

In Cleburne, Texas, the United States of America, Eden Green Technology built a high-tech nutrient film technology (NFT) vertical farming typology with LED lights for growing leafy greens. The plants are potted in modular cylinders, which, standing side-by-side, form rows. Eden Green grows in tubes that are shaped like winding vines. Through a partnership with Wal-Mart, they are the first commercial grower with enough scalability to meet the needs of regional food distribution systems. Eden Green Technology's products are planted, picked and packaged at the same location and shipped to the retailer in an uninterrupted cold chain, which reduces the risk of contamination.

figure 27: standing vertical farming typology (Eden Green, 2021)

Each crop is grown in a soil-free micro-climate; its own pod in the tubes of the standing system, free of pesticides, etc. The system uses sunlight instead of LED light, making production environmentally friendly and only one-eighth the cost of traditional greenhouse cooling. The system allows ten to fifteen harvests per year, compared to an average of two for open field farms. A stable climate reduces harvest losses to less than 1% (whereas the industry standard is 30%) (Eden Green, 2022). Such figures, equally impressive for many other vertical farming typologies, massively help to reduce food waste and increase the R&D progress in the food production sector; this increases food security by 2050, as discussed in p1 intro c1 food threats. Eden Green's system fits anywhere, as the pods can be stacked to form tubes as high fits. Something to note is that the crops grow on both sides of the tubes, so they must also be accessible from two sides.

graph 5: standing vertical farming typology FSI (own, 2023)

This means that some space must be maintained between the rows of tubes and a gable, whereas single-sided growing systems can be placed right next to a gable. Moreover, in a standing vertical farming typology, the rows are (preferably) as high as the greenhouse allows, and one must be able to reach the top, as the typology is static. Thus, even more space must be reserved to keep the crops accessible with an aerial platform. All in all, this typology is technically sound and sustainable, but not optimal to be used in a hybrid urban vertical farm. However, as is true for most of the typologies evaluated, this changes when multiple modules are linked. In fact, when multiple modules are linked together with this typology, no aerial platform entrance is needed for every row of 15 tubes, but only one for every (multi-module long) row of tubes.

Figure 28 shows how a standing system can fit into half a module. There is space for three rows of fifteen tubes, each of the tubes build from 24 stacked modular pods. One-and-a-half meters is kept clear between the gables, so an aerial platform can drive there. Along the rows 675 mm is kept clear, so an employee has enough space to reach between tubes and work crops on the other side. For larger module configurations, rows can be placed closer to the gables.

45 tubes x 24 pods; 1,080 crops are grown on the footprint of half a module. This gives a FSI of 1,080 / 506 = 213% This ratio is shown in *graph 5*.

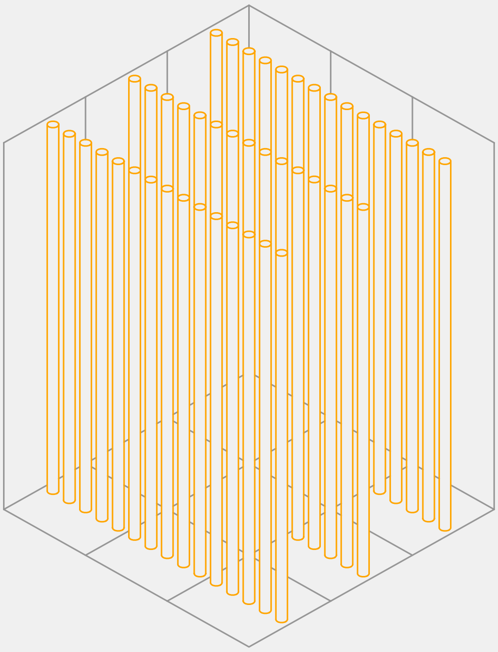


figure 28: standing vertical farming typology in half a module (own, 2023)

Two pros of the standing vertical farming typology are:

- *Lightweight structure*: the lightweight structure needed to keep the tubes upright can be build with the midfield columns from the case study, enabling reuse of components in the growing system too;
- *Modularity*: the modular nature of the standing system makes it possible to easily expand the growing system in height and width when a growers wants to increase its cultivation capacity.

Two cons of the standing vertical farming typology are:

- *Uneven daylight*: even though daylight is an advantage over using artificial light, in the standing vertical farming typology, daylight at the bottom is weaker than at the top, leading to uneven growth;
- *Crop density*: the crop density is low, even though vertically crops are only 25 cm apart, horizontally it is 1.5 m. An lower, (horizontally) denser growing system without an aerial platform would be better.

towering

There is a wide variety of small-scale, often modular vertical farm systems on the market. With Tower Farms, Agrotonomy is a major player in the field. Tower Farms is an automatically fed system. It can run on solely daylight, but shade and space utilization are pain points. Agrotonomy's Tower Farms are 100% automatically fed growing systems. The towers consist of modular discs, so towers can be as high as desired. Each tower stands on a base with a water pump. Tower Farms can be set up in a greenhouse or inside a building using grow lights. This system is hydroponic; after three minutes in water, roots dry in the air for twelve minutes.

figure 29: towering vertical farming typology (Agrotonomy, 2022)

The tower system appears to be self-contained, but each farm needs one or more irrigation systems to feed a group of towers. In addition to a variable-sized gravity tank (depending on the number of towers), there are two reservoirs, for two types of nutrients. A dosing system delivers units of each type to the water that comes out of the tank; the dosing differs per type of crop. Manifolds distribute the water to tubes leading to pumps in the towers. Each tower uses 3.8 liters of water per day. As for electricity use; each tower has a 50 W pump, totalling 450 watts for nine towers. A three minutes on/twelve minutes off regime means an operation time of 4.8 hours/day resulting in an electricity use of 2.16 kWh/day, costing €1.25 euro (Consumentenbond, 2022).There are Tower Farm systems for high-density (microgreens) and regular (e.g., leafy greens) crops.

graph 6: towering vertical farming typology FSI (own, 2023)

The latter is the baseline to compare the typology; for it, towers are available with seventeen stackable planting discs (height: 190 mm, diameter: 220 mm, capacity: four crops) (Agrotonomy, 2022). Two stainless steel rods provide stability inside each tower. Leafy greens and herbs do not outgrow the radius of the tower and thus do not need support from external structures. Including the reservoir with the pump (height: 360 mm, diameter: 730 mm, capacity: 70 liter), a tower is 2.1 meter high. Towers are available up to 2.9 meter high, but the top of those are not reachable by hand. Agrotonomy recommends an area of one to two m^2 per tower, therefore in the drawing an area of 1.5 m^2 per tower is used. In theory, the (small) irrigation system can just stand in the module, eliminating the need for a technical room.

Figure 30 shows how a towering system can fit into half a module. As earlier mentioned, grid slots of one-and-a-half square meters are reserved per tower, so there is space for nine towers only.

9 towers x 36 discs; 324 crops are grown on the footprint of half a module. This gives a FSI of 324 / 506 = 64% This ratio is shown in *graph 6*.

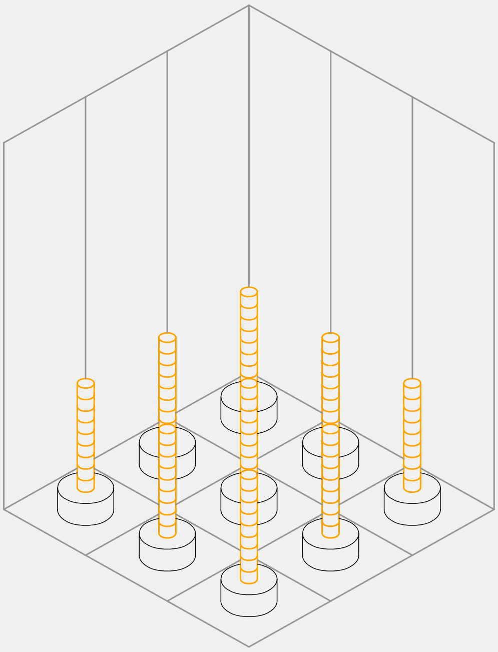


figure 30: towering vertical farming typology in half a module (own, 2023)

Two pros of the towering vertical farming typology are:

- *Accessibility*: no aerial platform is needed because the towers can be build by the employee who will harvest the crops, that person can make the tower as high as they can reach;
- *Extension possiblities*: because of the modular nature of the individual towers, a farm can be easily extended in height, as well as in general by connecting more towers to the irrigation system.

Two cons of the towering vertical farming typology are:

- *Space utilization*: because the towers are offered up to a height of 2.9 meters, a maximum of half of the six meters of free height in a huvf module can be utilized, thus wasting a lot of usable space;
- *Shadow casting*: despite the fact that the Tower Farm is designed to use daylight, surrounding towers cast shadows on lower-level discs, resulting in uneven exposure of crops over the height of a tower.

riding

To start a vertical farm, one does not need a high-tech system. Most growers are already familiar with *Danish carts*, movable layered transport carts. These lend themselves well to starting a vertical farm in combination with a simple lighting system. Every grower has a number of Danish carts. Naturally, there are then players on the market who see a gap in the underutilization of those carts, who know how to find a way to grow food efficiently with them. One such company is Avisomo, which offers growers a robot, the Lowpad M, that fits under Danish carts and drives them to a Growth Station. At the station, up to three carts are illuminated by artificial light on each layer (Avisomo, 2022).

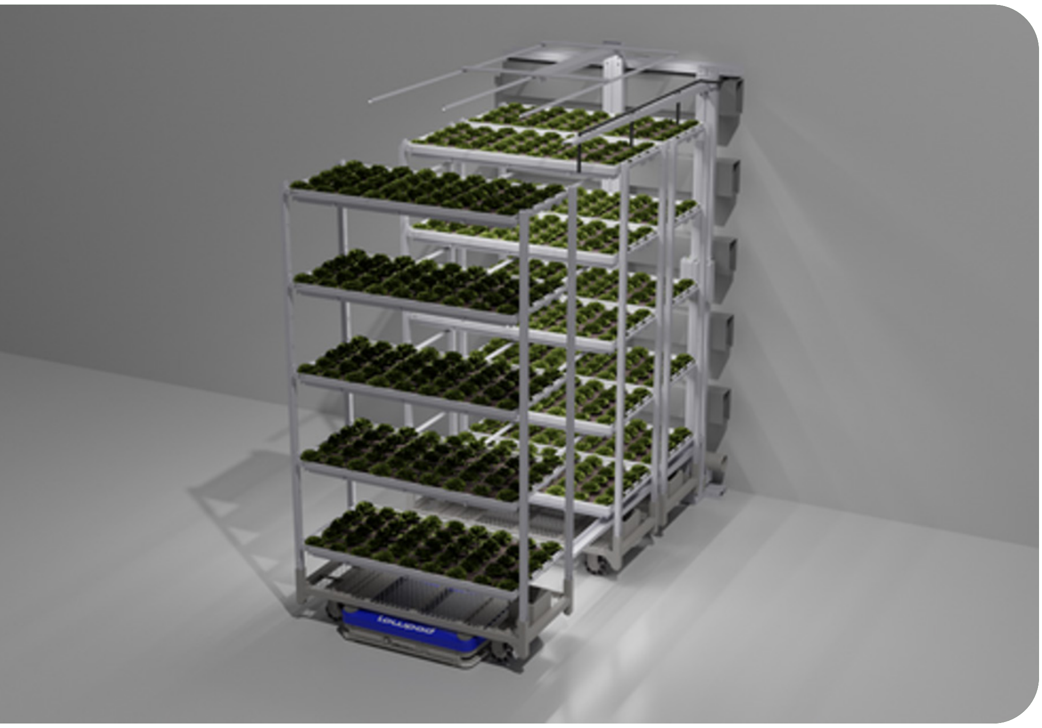


figure 31: riding vertical farming typology (Avisomo, 2022)

Avisomo offers three stations, first, the Research Station, a one-cart station for those who want constant monitoring and access to their crop. Second, the Growth Station 4E, a simplified system for a quick return of investment. This station works for carts that have three tiers and lots of space between trays, requiring less energy to run a system. However, the Station 4E is only suitable for basic crop recipes. The most advanced, third, the Growth Station 5E can handle any crop recipe and makes better use of space. It is set up for automated growth of high-end produce. With better lighting control, this system allows for advanced operations and allows fine-tuning plant health, taste, nutritional values, and appearance (Avisomo, 2022). In a riding system carts can be reused; growers can redeploy carts they own, because non of this systems' installations are mounted onto the cart.

graph 7: riding vertical farming typology FSI (own, 2023)

The cart is driven into a station by a robot that grabs to the bottom of carts. It is therefore possible to start a riding system without buying customized (new) carts. However, using Danish carts also has a disadvantage; they have a size of 1,350 by 565 mm, meaning that considerable free space is required for driving them around. The Avisomo E5 can illumniate three carts (1,350 by 1,695 mm) in an area of 1,500 by 2,000 mm. The system gets stability by fixation to a gable, allowing an efficient layout. To keep the system independent from a supporting construction, it can also be equipped with a base plate, however, this prohibits space-efficient configurations. The horticultural sector already has an advanced exchange system of Danish carts between growers, allowing more/less carts to be used during peaks and dips in production.

Figure 32 shows how a riding system can fit into half a module. Three Avisomo Growth Station 5E can be placed against the gable. As stated, such a configuration cannot be mirrored on the other side of the module, as that would not leave space for the robots to drive Danish carts in and out of the stations.

With nine carts of five tiers each, a total area of 11.4 m^2 is available to grow crops. Thus, in a module with the riding system, 285 crops can be grown. This gives a FSI of 285 / 506 = 56% This ratio is shown in *graph 7*.

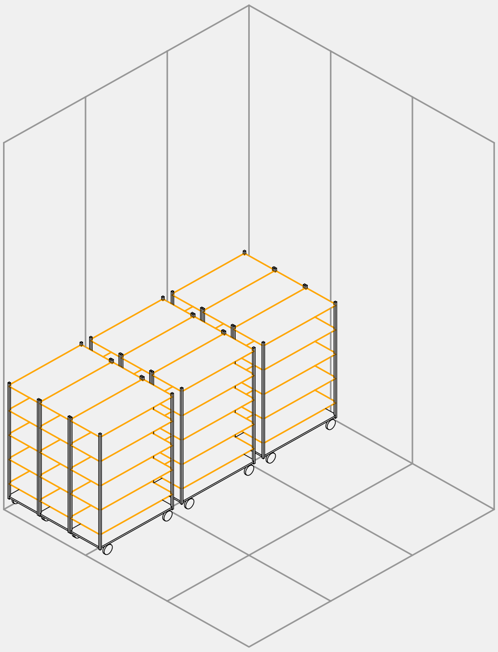


figure 32: riding vertical farming typology in half a module (own, 2023)

Two pros of the riding vertical farming typology are:

- *Redeployment*: virtually every grower already has Danish carts, so the investment cost in a driving system is relatively low because already owned equipment can be reused in a new application;
- *Low-tech*: despite using a robot, the system and its components are very simple and easy to repair, and the system's movements are minimal; in motion only when a cart must be accessed.

Two cons of the riding vertical farming typology are:

- *Low capacity*: because Danish carts with a standard height of 190 mm are used, and there must be a minimum clearance between crop and light, the vertical capacity is limited;
- *Artificial lighting*: the 400 mm height between tiers of Danish carts requires artificial lighting, especially with the large enclosed area that several contiguous carts form.

hanging

If a structure is strong enought to carry it, it is possible to place a system not on the floor, on rails, but suspended it from the roof on rails. This is often done with smaller vertical farm elements, such as tubes, which together form a wall, but can be moved individually. Just outside Plenty's artificially lit farm, a robot picks up seedlings and plants them in a hydroponic tube. A little further along, a second robotic arm flips the tube vertically and hangs it in rails overhead.The combination of efficient space use and multiple harvests per year allows Plenty to grow as much produce as a one-layer system could on an entire soccer field on the footprint of a single goal (Agritecture, 2019).

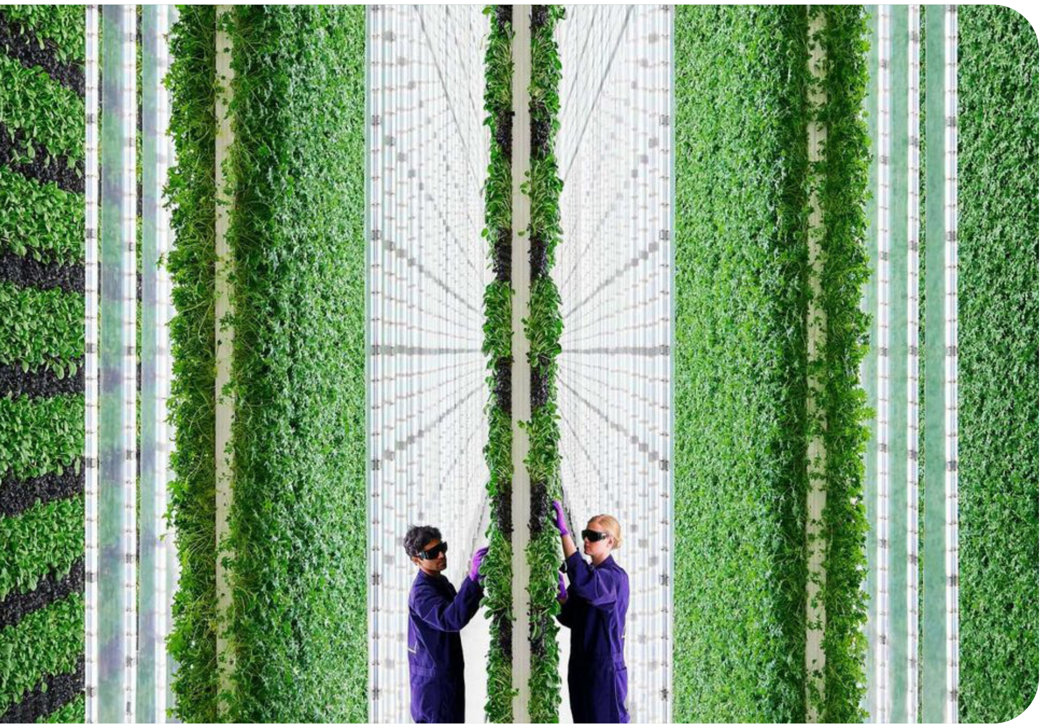


figure 33: hanging vertical farming typology (Agritecture, 2019)

Plenty's is one of the few commercial farms that use a hanging system; little technical information has been published on how these farms supply plants with the necessary resources. In general, this typology uses pipes suspended from overhead convectors. The advantage is that the tubes (thus the crops) can be close together during the early stages of growth, while at later stages the conveyor allows tubes to be spaced further apart. As the tubes are tall, (un)loading the towers to and from the overhead conveyor with robots is a common approach to manage the transition from floor level to above. Farms with hanging towers can have towers more than nine meters high. Vertical conveyors in this size can be motorized or hand-pushed. The system can be automated, which is recommended for larger commercial farms; because of economies of scale, it then costs less per meter rails.

graph 8: hanging vertical farming typology FSI (own, 2023)

It is easy for farmers to later expand an existing manual system with drive motors. As for maintenance; the drive system originates from the automotive industry, where maintaines are done twice a year by a certified company. As the vertical farm application of the simple, robust system is used less intensively, maintenance can be done even less routinely. In this typology analysis, and in the drawing, a manually driven overhead rail system was assumed, because the system must also be able to operate in a single module, and it does not then make sense to build an automated system for 45 tubes only. If several modules are to be linked, auotmization can still be integrated at a later stage.

Figure 34 shows how a hanging system can fit into half a module. There is space for three rows of fifteen tubes, each of the tubes has a capacity of 24 crops. A path of one-and-a-half meters is kept free between the rows, so that an aerial platform can drive there. Along the gables 675 mm is left, so an employee has enough space to reach between tubes and work crops on the other side. For larger module configurations, walls can be placed closer to the gables.

45 tubes x 24 crops; 1,080 crops are grown on the footprint of half a module. This gives a FSI of 1,080 / 506 = 213% This ratio is shown in *graph 8*.

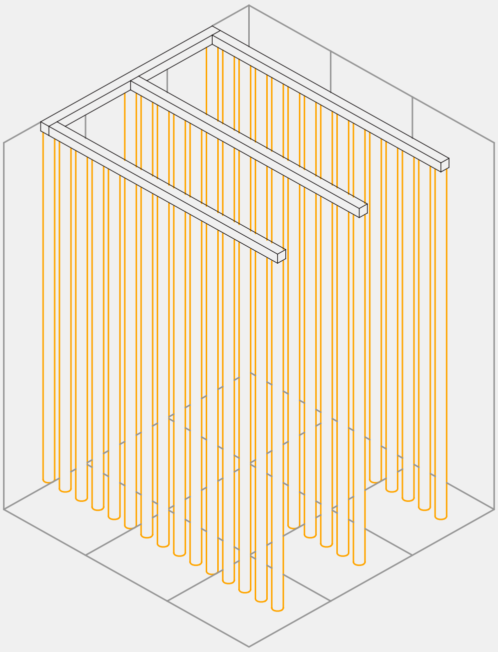


figure 34: hanging vertical farming typology in half a module (own, 2023)

Two pros of the hanging vertical farming typology are:

- *Manual operation*: because each lightweight tube can be moved separately, workers can pull tubes around indidividually. This does not require robots or central control, allowing flexible working;
- *Customizable spacing*: because every tube can be moved separately, young crops can be spaced close together, and older/larger crops can have more space between them so they do not obstruct each other.

Two cons of the hanging vertical farming typology are:

- *Accessibility*: because the system is very high, a robot is required to get crops from the higher regions to a workable height, because an aerial platform will not fit between the paths;
- *Eye comfort*: since this system uses bright pink artificial light it is required for employees to work with sunglasses on, which decreases human comfort in the workplace.

racking

When growing crops vertically, the easiest way is a racking system. Just like in a warehouse, the goods, now crops, lie one above the other in racks. If a tray has to be picked, one has to go up with an aerial lift in this passive system. Since 2004, AeroFarms has been the commercial leader in indoor vertical farming, uniquely using proprietary aeroponics to optimize growth while using up to 95% less water and no pesticides. Aerofarms' farms are built in halls in and around major cities, close to major distribution routes, allowing fresh food to be produced year-round and distributed locally on a large scale (Aerofarms, 2023). Aerofarms' racking system consists of a slender columns and girders structure.

figure 35: racking vertical farming typology (Aerofarms, 2023)

Placed within are containers in which leafy greens grow. Along the construction run pipes that supply water enriched with nutrients that is atomized into the containers; an aeroponic system. The container bottom collects precipitated water and drains it into a discharge pipe, ready for reuse. No herbicides, pesticides, germicides, and insecticides are used. Because the crops are grown on a patented reusable cloth medium (from recycled water bottles), the roots are not surrounded by a growing medium, but they hang free and have access to oxygen. Twenty-six harvests a year and a high FSI make Aerofarms's racking system 390 times more productive than open field farming. The racking system must be irrigated, in Aerofarms' system by aeroponics. However, since the crop density in one rack is very high (requiring a lot of water), it does not make sense to combine the racking system and the irrigation system in a single module.

graph 9: racking vertical farming typology FSI (own, 2023)

The irrigation system would then get in the way of the racking system and drive equipment (e.g., an aerial platform). Aerofarms' system is optimized for its containers, the columns and beams fit exactly. So in the drawing, that system cannot be copied one-to-one, because the racking system here must fit into the modules that were designed in p3 module c3 design. As a racking system is too slenderly dimensioned anyway to reuse RHS steel from the case study, this is not a problem: new (slender) steel can be cut to custom size. Naturally, that zou de carbon footprint van het growing system verhogen. In larger module configurations, contrary to what the drawing shows (which is designed for one module), there can be more than one racking system per half-a-module, because walkways that are shared between seperate racks.

Figure 36 shows how a racking system of ten layers can fit into half a module. To have a handleable system, the containers of 1,500 mm wide are divided into removable trays of 750 by 500 mm. For one module, this layout is the maximum occupancy, as an aerial platform must be able to drive around the cabinets, to keep the crops on the upper layers accessible. For larger multi-module systems, that space can be shared, so a connecting module can have two racks of ten layers.

With ten layers of 4.5 m^2 each, 1,125 plants are grown on the footprint of half a module. This gives a FSI of 1,125 / 506 = 222%. This ratio is shown in *graph 9*.

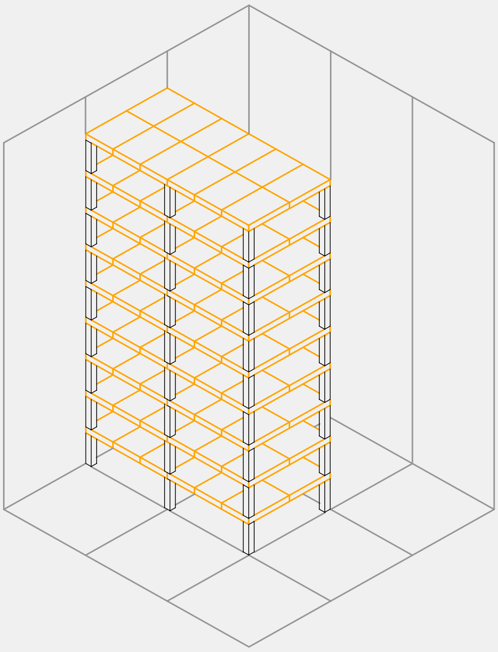


figure 36: racking vertical farming typology in half a module (own, 2023)

Two pros of the racking vertical farming typology are:

- *Accessibility*: even though an aerial platform will be needed regularly, all crops are always accessible: there is no need to first shift or rotate the system;
- *Efficiency*: as long as a margin of 40 cm is maintained between the containers and the LED light, the racking system can be extended in height as far as the free height allows.

Two cons of the racking vertical farming typology are:

- *Reuse*: a lightweight racking system can suffice with an elegant construction, it makes no sense to increase the reuse rate and apply columns of 160x60x4 midfield (case study) for the racking structure;
- *Height*: since a racking system is static, growers need to use a aerial platform or similar equipment to reach the upper croptrays. This takes workspace and incurs energy costs for machinery.

sliding

Any previous system required workspace, which takes away space that could be put to good use. A sliding systems solves this: sliding racks now require only one work path. Don’t need access to plants? Slide them against each other! Efficiency. A supplier of sliding systems is Montel, also a well-known provider of cabinet systems in archives, libraries, universities, and pharmacies. So the technology has been tested and developed in many fields of work. This system utilizes all available space; there is no reason to grow less efficiently than the footprint allows: only one aisle is needed. It increases efficiency both horizontally and vertically, as the cabinets can be made as high as fits. (Montel, 2023).

figure 37: sliding vertical farming typology (Montel, 2023)

The cabinet systems, particularly when loaded with propogation trays and crops, are heavy and difficult to operate by a single human. Therefore, by pushing a button or a lever (or even by sliding a system to the desired position in an app), cabinets can be moved automatically. Although Montel does not provide climate control for vertical farms, their system is designed to fit artificial LED lighting, ventilation systems, and hydrological high-efficiency growing methods. In addition, the multilayered shelving systems can be adjusted so that the aisle provides space for any aerial platform, to access crops in vertical plane. The rail system is embedded in the floor, this is increasing the stability of the cabinets; cabinets that slide on rails that are mounted on-floor instead of in-floor are at risk of collapsing horizontally as a result of the absence of support. Montel systems are delivered as a welded unit (Montel, 2023).

graph 10: sliding vertical farming typology FSI (own, 2023)

This is undesirable for the growing system designed in this thesis, but that does not mean that the techniques and principles behind the Montel sliding system cannot be combined with reusable steel components from the case study. As long as the maximum load of the sliding base of the system is taken into account, and racks placed on it are properly connected to the base, the racking on which containers with crops are stores can be manufactured from reused columns.Therefore, in the drawing it was chosen to make the structure of 160x60x4 mm midfield columns, in order to easily get an estimate of the available growing area when the dimensions of the available columns are normative. This results in a slightly lower efficiency than if a more slender construction had been used.

Figure 38 shows how a sliding system of two racks of ten layers each can fit into half a module. For one module, this layout is the maximum occupancy, as an aerial platform must be able to drive between the cabinets, a space of 1,500 mm is kept open. In bigger module configurations, that space can be shared, so a connecting module can have another three racks of ten layers, almost doubling the footprint efficiency.

With twenty layers of 4.5 m^2 each, 2,250 plants are grown on the footprint of half a module. This gives a FSI of 2,250 / 506 = 444%. This ratio is shown in *graph 10*.

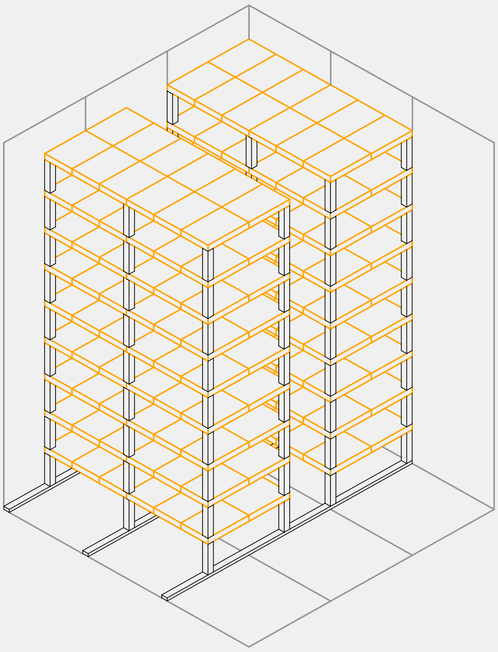


figure 38: sliding vertical farming typology in half a module (own, 2023)

Two pros of the sliding vertical farming typology are:

- *Space utilization*: because the cabinets can slide there is only a need for a working path to reach plants at all times, this ensures that more square footage can be utilized;
- *Reuse possible*: even though elements in a Montel sliding system are sized differently than compenents from the case study, slender midfield columns can be used in the rack construction.

Two cons of the sliding vertical farming typology are:

- *One-sided daylight*: when cabinets are side-by-side, only natural daylight can enter through the short sides of the cabinets, this significantly reduces the already minimal daylight level in the layers;
- *Accessibility*: it remains a pain point, but tall systems that do not automatically bring their layers from top to bottom and thus require an aerial platform are detrimental to energy use and space consumption.

rotating

Every system so far had one of two major problems: either the system was low enough that one could reach everything, but this prevented efficiency. Or it was high and required an aerial platform. This system does both: it rotates the bins to a workable height. In 2009, Sky Greens' founder began building vertical farm prototypes from aluminium frames; in 2012, commercial cultivation of tropical leafy greens began in the unique rotary system in Singapore. It is a low-carbon system in which trays with crops rotate along a chain in the A-frame. An economical low-pressure hydraulic water drive, combined with the use of gravity and a lightweight construction make the system energy efficient and sustainable (Sky Greens, 2014).

figure 39: rotating vertical farming typology (Sky Greens, 2014)

The system can be nine meters high (38 containers). Those rotate so that each crop is exposed to an equal amount of sunlight, nutrition and water. Frames are placed in a controlled environment, to achieve quality in a stable climate. In Singapore, sunlight eliminates the need for artificial light. Only 40 Watt is needed to power one tower. Water consumption is minimized: crops are fed with a hydroponic flooding method, eliminating the waste of, say, a sprinkler system. Because the A-frames are placed in a protected environment and the applied stresses on the structure are low, maintenance of the system is minimal.In Singapore there is intense sunlight, the Sky Greens system can saturate the light requirements of plants there by just rotating containers to sunlight. In less favorable regions, the light sum that plants can reach during a day will be lower, here supplementation with artificial light will be required.

graph 11: rotating vertical farming typology FSI (own, 2023)

The construction of the Sky Greens system provides space between the rise and fall of rotating containers to place artificial light. To provide plants with as equal a climate as possible, the system should rotate at such a rate that changes in sunlight intensity (due to time lapse and cloud cover) have minimal effect. A circulation of once every half hour for a 5 meter high system with containers that are spaced 1m center to center (thus a total chain lenght of 12m) this means a rotation speed of 3.3 mm/s; which is deemed safe to work around. The economical low-pressure hydraulic water drive could be replaced any other drive motor, making it possible with a rotating system to reuse the drive motors that normally open the ventilation windows in a greenhouse for this purpose.

Figure 40 shows how a rotating system can fit into half a module. There is space for six A-frames. Multiple frames can be connected to one drive motor, for this drawing it assumed that one drive motor powers three A-frames. In the middle, 1.5 meters is reserved as workspace. For one module, this is maximum occupancy, as employees must be able to walk in between. For bigger module configurations, workspace can be shared.

With six frames, each holding 20 containers of 0,42 m^2 each (50.4 m^2 in total), 1,260 plants are grown on the footprint of half a module. This gives a FSI of 1,260 / 506 = 249%. This ratio is shown graphically in *graph 11*.

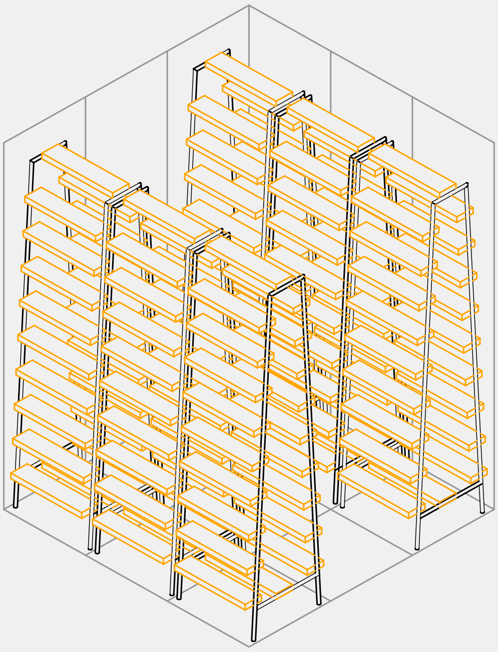


figure 40: rotating vertical farming typology in half a module (own, 2023)

Two pros of the rotating vertical farming typology are:

- *Mechanics*: the rotating system, in the case of Sky Greens, runs on a single driven chain on which trays are balanced, rotating with a low-pressure hydraulic water driven system - low-tech is often robust;
- *Accessibility*: no matter how high the rotating system is, because it rotates, each tray automatically returns to workable height, so employees are not forced to go up by themselves.

Two cons of the rotating vertical farming typology are:

- *Footprint*: in the case of Sky Greens' rotoating system, the structure fans out downward, requiring a lot of floor space, while in the horizontal plane only two relatively narrow containers are returned;
- *Drive motors*: since the growing system must run continuously, a lot of drive motors are required to keep rotating each A-frame (possibly in intervals), which over time will tick up in electricity consumption.

summary

Graph 12 summarizes the nine analysed vertical farming typologies. On the left, for each typology the FSI is given, these bars are scaled to allow a comparison between systems. On the right, all typologies are given a summed ranking based on the number of positive icons that are assigned to them. For each set of icons, one was designated as the one that is more positive for the sake of durability, ease of use, longevity, etc.. The reasons for the prefered icon (the non-striken through) is:

- Naturally lit/~~artificially lit~~: as this decreases the energy use of a system;
- Low-tech/~~high-tech~~: as this decreases the maintenance of a system;
- Manual/~~automatic~~: as this decreases the required skills to operate a system;
- Self-supporting/~~supported~~: as this takes away the need for additional construction;
- Dynamic/~~static~~: as this takes away the need to move individual trays by hand;
- Accessible/~~unreachable~~: as this takes away the need for an aerial platform;
- Modular/~~stand-alone~~: as this enables easy (future) extension of a system;
- Possible reuse/~~new materials~~: as this decreases the carbon footprint of a system

Positive icons represent the more energy efficient, workable, easily expandable and simpler constructable of each set. These characteristics are desirable for the growing system that will be designed for a hybrid urban vertical farm in p4 system c3 design. Positive icons are green, negative icons red. The number of positive icons that is assigned to each vertical farming typology is summed on the right side of *figure 41*. The higher the score, the higher its generic suitability for the growing system that is to be designed. The result: it is clear that a sliding system is the most space-efficient, with a FSI of 444% it scores almost double the second best vertical growing typology (rotating; 249%). The typology with the most desirable characteristics for a sustainable, easy to use and accessible growing system is the rotating system with a score of eight out of eight. These results are included in the conclusion.

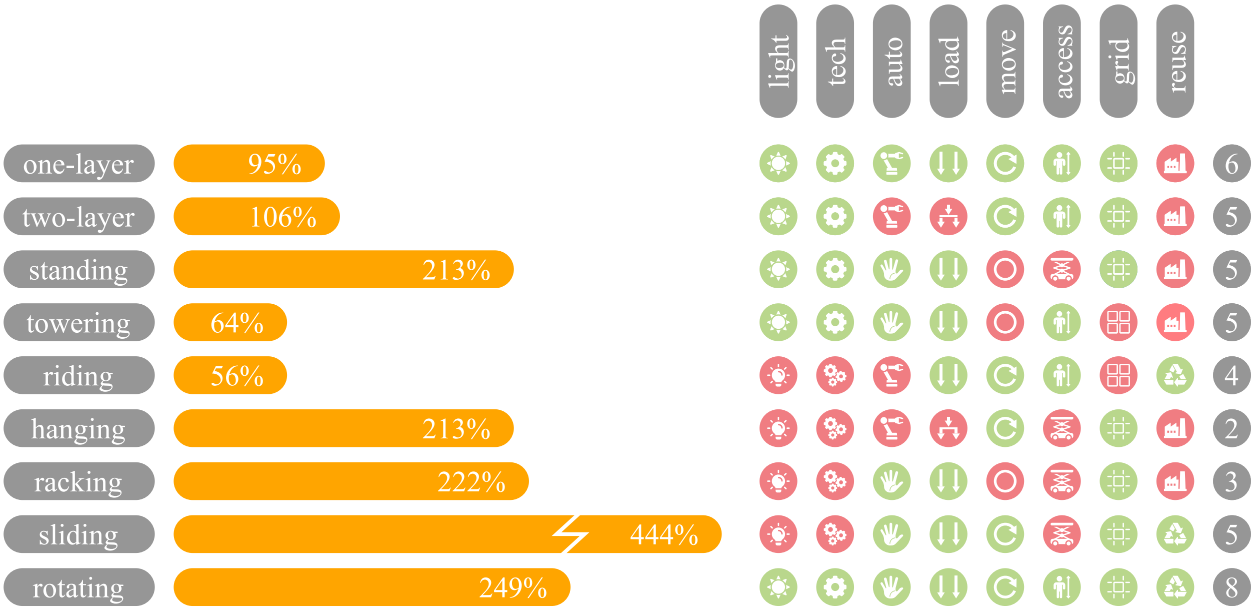


figure 41: vertical farming typology analysis overview (own, 2023)

conclusion

Almost every vertical farming typology has the disadvantage of requiring workspace around them, either for an employee to walk there or for an aerial platform to drive around it. The sliding system is the ideal solution for this; it is also directly visible in the floor area index, which is the **highest** of all analysed typologies, of 444%. An aisle is still required for an aerial platform, but it has to occur only once in an entire row of connected modules. The location of the aisle can be changed by sliding cabinets to another position, away from the cabinet that one wants to work with. Drawbacks are that the sliding system operates on artificial light due to the closed nature of the cabinets, and as mentioned, it requires an aerial platform.

Fortunately, there is Sky Greens' system, which provides a way to improve the sliding system, which is limited in its current state. One pro is that a rotating system brings crops to workable heights for employees without any mechanics outside the system (e.g., an aerial platform). meaning that not all the light needed for crops must be artificially supplied. The sustainable character of the rotating vertical farming typology is reflected in its sustainability assessment, as it is the only typology that scores **eight out of eight** on the summed sustainable features.

When combining the results of the typologies that score best on the FSI assessment and the sustainability assessment, respectively a sliding typology and a rotating typology, the key to design a space efficient and sustainable growing system is revealed. The design-task for p4 system c3 design is to design a rotating growing system that is mounted on rails, so it can slide. This eliminates both the need for an aerial platform and for workspace next to every growing system so the number of crops per m^2 can be higher. To bring down the carbon footprint of the design, and not rely on newly manufactured materials like many of the studied vertical farming typologies do, the toolbox of reclaimable components from MightyVine phase 3 is considered as considered as construction materials for the construction of the growing system.

The research conducted in this chapter has been integrated in the design of a hybrid urban vertical farm. Now, at its conclusion, references are made to the chapters in which the features identified as important in this chapter have been incorporated into the design.

- The conclusion of the vertical farming typology analysis is the starting point of the sliding and rotating growing system designed for the hybrid urban vertical farm (p4 system c3 design);
- To include components from the midfield of MightyVine phase 3 that are not reused in the modules, the drive motors that open ventilation windows in the greenhouse are reapplied to drive the rotating system (instead of the water-driven motor of the Sky Greens vertical farming typology) (p4 system c3 design);
- To make the design as sustainable and easy to use as possible, it meets all eight characteristics belonging to the eight positive icons: naturally lit, low-tech, manual, self-supporting, dynamic, accessible, modular, and reuse is possible (p4 system c3 design).

in this chapter

This chapter explains in step-by-step manner how the design of a sliding and rotating growing system, the innovative alternative to existing verticalf farming typologies was achieved. From propogation tray to drive, and from construction to irrigation. Finally, it is determined whether the construction of recycled midfield columns is strong enough to support the designed containers.

approach

Before the build-up of the growing system, a simplified version of is shown in *figure 42*. It is 1,460 mm wide and 2,350 mm long. When placed in a configuration with the minimal depth, 4,500 mm, one growing system can be placed to leave walkspace **next to** the growing systems of 4,500 - 2,350 = 2,150 mm. Modules can be linked to form configurations with a bigger depth; e.g., configurations of two bays deep have a depth of 9,000 mm. If three growing systems are placed in them, 9,000 - 2,350 - 2,350 - 2,350 = 1,950 mm is left for two walking aisles of 975 mm wide. This is unsufficient to comfortably pass other employees and/or materials to work on the crops. However, it is likely that growers will actually build module configurations that are a multitude of two bays deep, as that results in space-efficient module configurations (proved in p5 optimize FSI), so a solution to prevent the walking aisles to be unsufficiently small had to be found.

That is why two types of growing systems are designed: first, a *single system*, in which sixteen containers rotate between two columns, stabilized with one bracing, and driven by a drive motor. Second, a *couped system*, in which 32 containers rotate between three columns (one columns is shared), stabilized with two bracing, and driven by one drive motor, Coupled system are 4,250 mm long. These are depicted in *figure 42*. By using a drive motor to rotate 32 containers instead of only sixteen , the number of drive motors required to operate the systems in an entire module configuration is reduced. When the calculation of the space that is left in the module is redone, now 9,000 - 2,350 (one single system) - 4,250 (one coupled system) = 2,400 mm is left, which is enough to create a comfortabel aisle on which employees and materials can passed. By using coupled systems, not only are less drive motors required, but there is also more comfort for the employees. To waste as little space as possible for workspace **between** growing systems, single and coupled systems form *system lines* in which they can slide on rails to create workspace elsewhere.

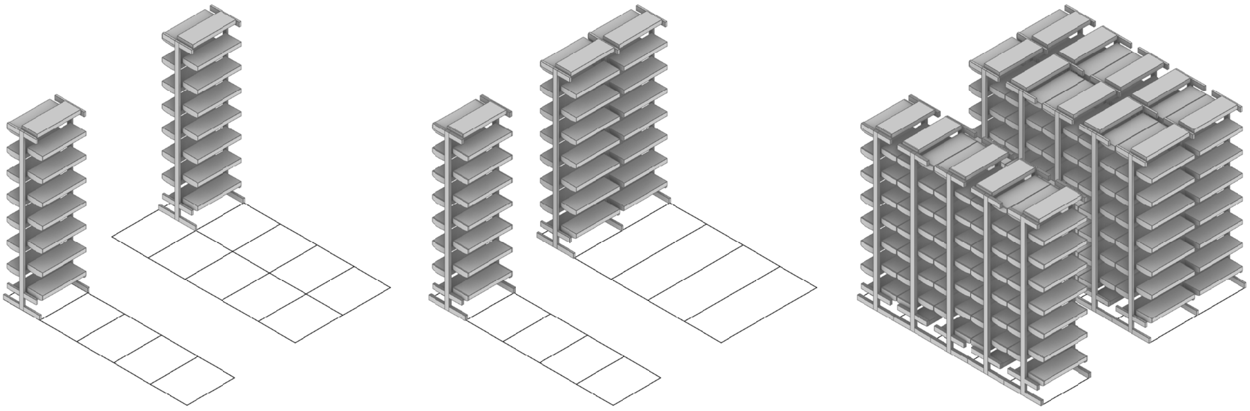
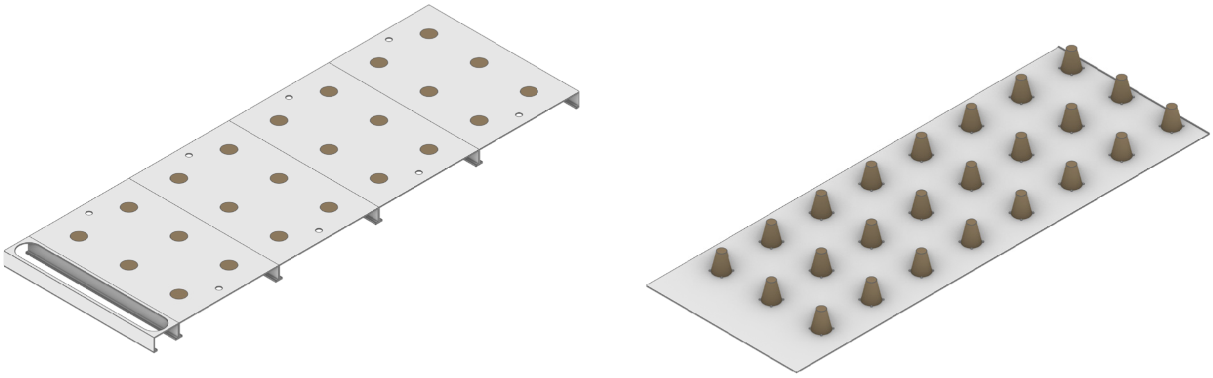

two single systems *a single and a coupled system* *a single and coupled system line*

figure 42: single and coupled systems form system lines (own, 2023)

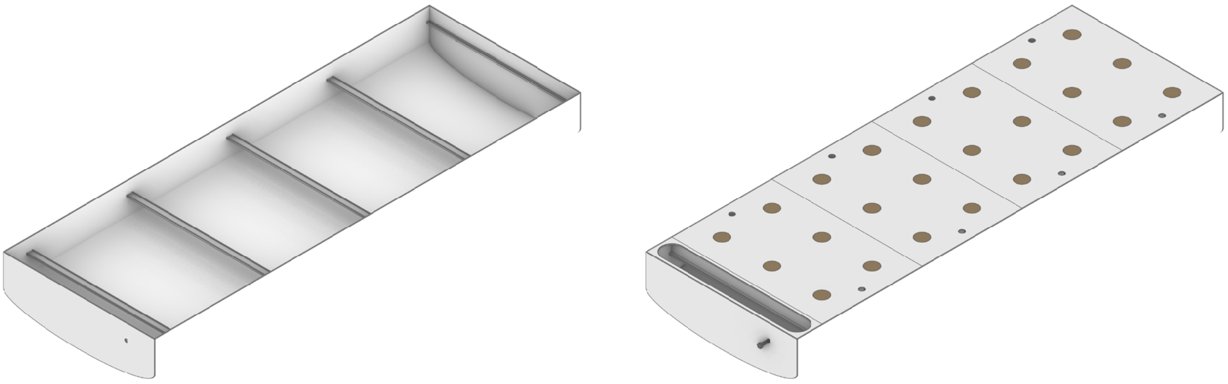
propogation tray

The growing system for a hybrid urban vertical farm is designed with the literature review of crop needs, the analysis of vertical farm typologies, and human comfort in mind. Everything in the design stems from the design of the component that employees will actually work with: the propogation tray. The propogation tray is designed from the question: *an object of which dimensions can a carry comfortably?* The horticultural sector has been thinking about this for years, and in that sector a tray of 400 mm wide and 600 mm long is the answer to that question. The longest side of 600 mm is comfortable to carry at shoulder width. Therefore, the trays in the system are 400 by 600 mm wide. Each tray provides space for six crops; based on the 200 mm in either direction that a head of lettuce needs. To not rotate every single tray individually, , four trays are placed side-by-side in a container, creating a growing surface of 600 by 1,600 mm, or 0.96 m^2, per container. To keep propogation trays fixed in place in a container, they are supported by aluminium profiles that span the container in the short direction. The raised edges on the sides of these profiles prevent the trays from sliding in a container, even if there are only one, two, or three trays in the four available tray positions. This principle is visible in the top left and bottom left in *figure 43*, which also show how the irrigation slot, is fixed by those aluminium profiles. The top right shows the NFT plate, which is discussed next, and the bottom right shows the container as it looks when it is completely assembled.



propogation trays with mosswool clods

NFT plate with mosswool cillinders



container with aluminium profiles

complete container

figure 43: container (own, 2023)

nft

The crops in containers are fed with a hydroponic NFT system in which the roots of the crops are suspended on a plate, the NFT plate. Because an NFT system works best with a film layer of water 2-3 mm, a raised edge of 2.5 mm high is placed at the end of the NFT plate. When water flows over the plate through the irrigation slot, all water above 2.5 mm high will flow over the edge and be drained into the container. If the supply of irrigation water stops, then the layer of 2.5 mm height will remain in the container until it is completely absorbed at by the roots, or evaporated. Within an hour the crops will receive water and nutrition again, this is discussed in the calculations at the end of this chapter.

mosswool

Crops grow in mosswool clods, a sustainable variant of mineral wool made from sphagnum moss, harvested using a new technique in which only a top layer of the moss is skimmed off so that the resource can regrow without damage (Cordis Europe, 2020). Young plants, seedlings, that have not yet developed long roots cannot yet reach the water on the NFT plate with their roots. Therefore, small studs have been placed on the NFT plate between which moss wool cylinders can be placed which connect to the bottom of the moss wool clods in the trays. Thanks to the capillary action of the airy material (similar to self-priming mineral wool), water and nutrients can be made accessible to the small roots. Once plants are large enough then the trays can be removed from a container with a NFT plate with studs and capillary moss wool cillinders, and placed back into a container with a smooth NFT plate. There, the roots can hang freely on the plate and absorb water and nutrients directly. This principle is shown in *figure 44*. It shows that below the irrigation slot there is a hole in the container bottom. Water enters through the irrigation slot onto the NFT plate, then overflows on the other side of the container, and drains through the container bottom into the hole.

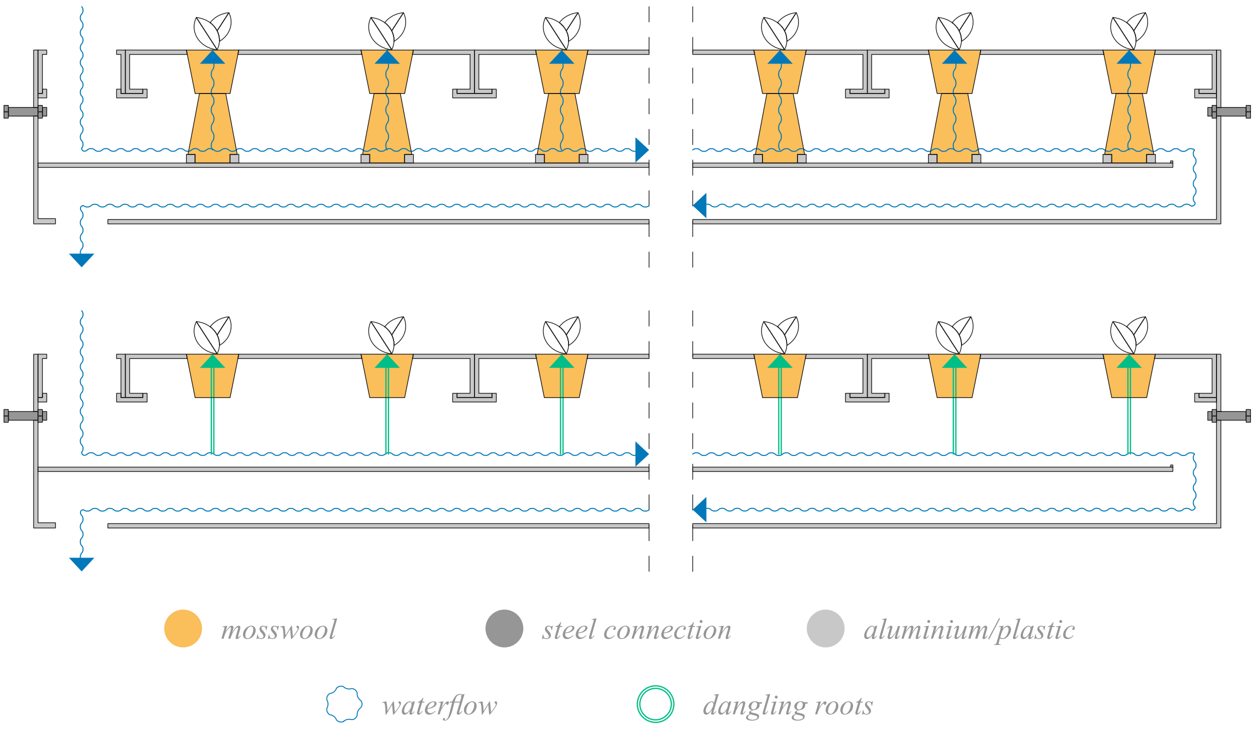


figure 44: NFT irrigation (own, 2023)

When multiple containers are suspended one above the other in the system, the drain holes are positioned exactly above the irrigation slots. Thus, dripping water will never fall on the crops, but instead will fall into the irrigation slot of a container below to irrigate those crops; water that still is not uptaken will be drained, to another container, of to the draining profiles that lead back to the technical room. Since the radius of the drainage hole is smaller than the width of the irrigation slot, it is impossible for water to drip on the leaves and lead to damage. How the NFT principle and the drainage of water works for both young plants without roots (i.e., with cappilary mosswool cylinders) and mature crops is illustrated in *figure 44*.

shape study

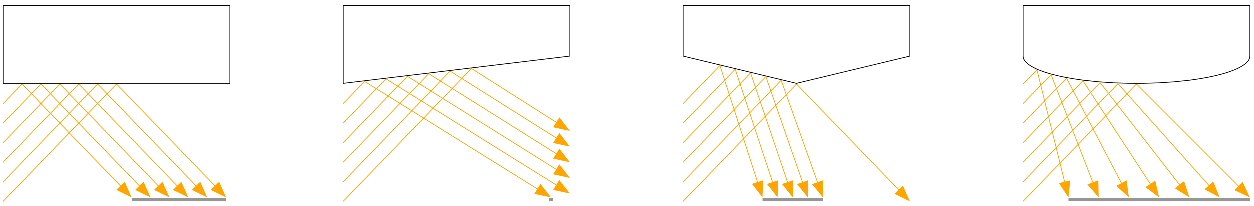
The choice for a container with an elliptical body results from four shape studies conducted to four body shapes; a *flat*, *angled*, *triangular*, and *elliptical* body. Two studies involve the balance of mass, the first study (row 1 of *figure 45*) first shows the paternoster suspension points center line. In a stable system the center of mass of a container is on/close to this line. The second study (row 2 of *figure 45*) shows the center of mass line for each body. In an angled body, it is shifted from the paternoster suspension center line.

paternoster suspension points center line

center of mass line of containers

center of mass line of containers plus draining water

NFT plate fitting into containers



illuminated area by reflection

figure 45: container shape study (own, 2023)

The third study (row 3 of *figure 45*) shows a similar study, now with draining water in the container during/after irrigation. In an angled body the water is collected off center, moving the center of mass even further away from paternoster suspension center line. For balance, an angled body is the worst, and a flat body is inferior to a triangluar and elliptical body, because the former distributes the water over the entire width, and the other two collect the water close to the paternoster suspension center line, thus increasing balance. The fourth study (row 4 of *figure 45*) shows how a 600 mm NFT plate fits any shape, under the condition that the plate sits 130 mm below the top of the container (50 mm of mosswool clods plus 80 mm for roots to dangle). This study does not indicate better/lesser shape, as the NFT plate fits any shape because the body differentiations only start below it. What is decisive is the fifth study (row 5 of *figure 45*): all shapes reflect light onto a smaller area than the elliptical body does. The latter, due to its curved shape, has many different angles of ingress and egress, reflecting light more widely and evenly on crops. In practice, the angle of incidence varies constantly, but the reflecting behavior of the various bodies will be approximately similar for different angles of fill.

Conluding, as an elliptical body, <u>first</u>, has a center of mass (with/without water) aligned with the paternoster suspension, <u>second</u>, can fit a NFT plate, and <u>third</u>, reflects incident light the most evenly onto underlying crops, the elliptical bottom is chosen over the flat, angled, and triangular body in the container design.

paternoster and chain

Containers have M10 bolts in the fronts, as is visible in the bottom right of *figure 43*. There is a bolt in each front, both are attached to chains that move at equal speeds. The chains have an 380 mm between each other, so the center of the containers is aligned exactly between these two chains. The rotating system that is created this way is called a *paternoster system*. It has been considered to reuse more horticultural materials in than only columns and bracing in the design of the growing system, such as forklift chains. However, forklift chains are leaf chains that are used for lifting, not for power transmission, like roller chains. Thus, it was decided to use roller chains.

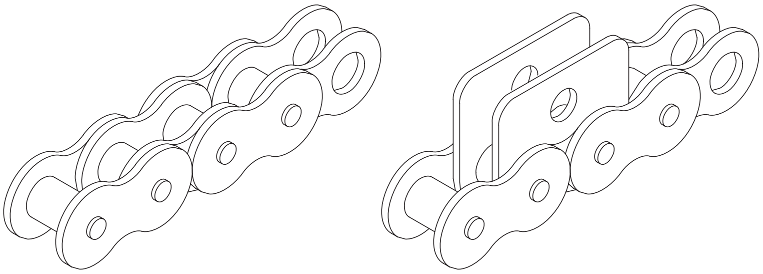


figure 46: rolller chain link types (own, 2023)

In the roller chain two types of links occur: *standard* and *connection* links. To the latter the bolts of containers are connected. Between connection links (40 mm) there are nineteen standard links (760 mm). This leaves 615 mm of free space between the bottom of a 185 mm high container, enough for crops to grow without touching the bottom of the container above them when the containers change from a vertical to a horizontal movement in the corners of the system. Also, this leaves enough room to keep around 450 mm of space between the top of crops and artificiall light, as is advised in vertical farming (van den Berg, R. & van der Velden, M. [Artechno], personal communication, January 09, 2023).

drive

The roller chains are driven by reused ventilation window drive motors. Because a hybrid urban vertical farming module is much smaller than the greenhouse from which components come, this will be proven in p5 optimize c3 columns, there is a large number of windows not reused. This mean drive motors can be reused in another function. In a coupled system, one drive motor drives two sets of sixteen containers. Power is transmitted with a drive shaft, also reused. With a belt, power is transferred from the shaft to a sprocket. That drive shaft-sprocket connection is as short as possible for the most efficient power transfer; hence the corner of the roller chain that is closest to the drive shaft is connected. The other three corners have chain cheaves which guide the roller chain. How the drive is connected to the structure and how the drive of a single system looks isolated is presented in *figure 47*. Closeups of the sprocket drive and chain sheaves are shown in *figure 48*.

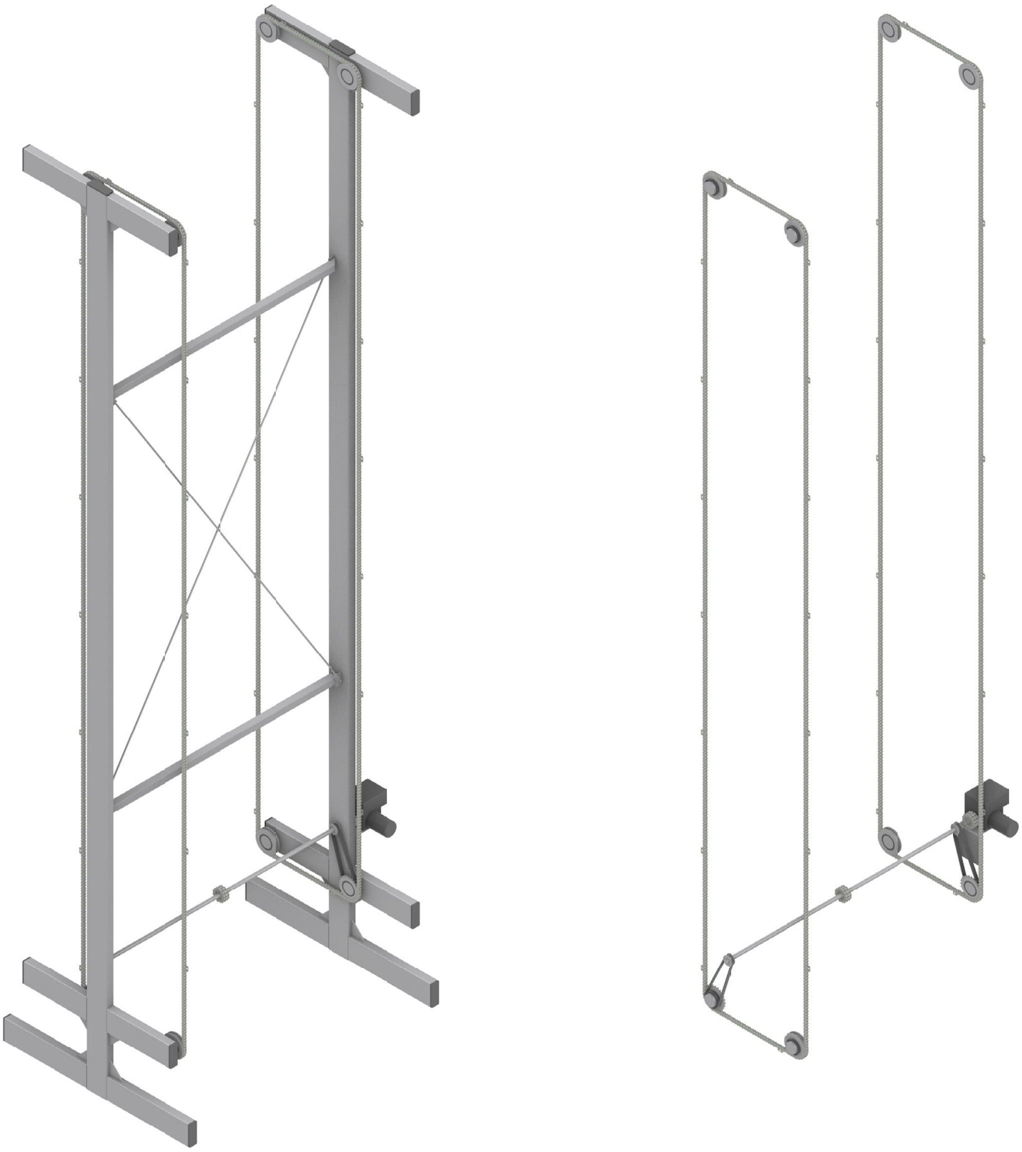


figure 47: structure with drive (l) and isolated drive (r) (own, 2023)

structure

The construction of the growing system reuses midfield columns of MightyVine phase 3. Because in a module configuration the most reused type of columns are gable columns, there are many midfield columns left to reuse for other purposes (like ventilation window drive motors), especially since most of the midfield of a case study greenhouse will not be reused anyway. The structure exists of *vertical* columns that carry the load of the containers, *arms* that hold the sprockets and chain sheaves and thus create the rectangular path along which containers rotate, and *feet* that provide stability at the base of each system. These elements can be made by resizing midfield columns into smaller pieces, as is illustrated for a single and a coupled system in *figure 49* and *figure 50*. How midfield columns can be optimally reused to create as many new parts is discussed in p5 optimize c3 columns. A vertical is 6,140 mm high, and as systems are meant to be placed on rails between trellises, there will be no interference of the construction of the system (and containers on the top position of the system) and the construction of the modules. An arm is 490 mm long, and a foot 640 mm long. The structure of a system uses bracing to provide horizontal stability.

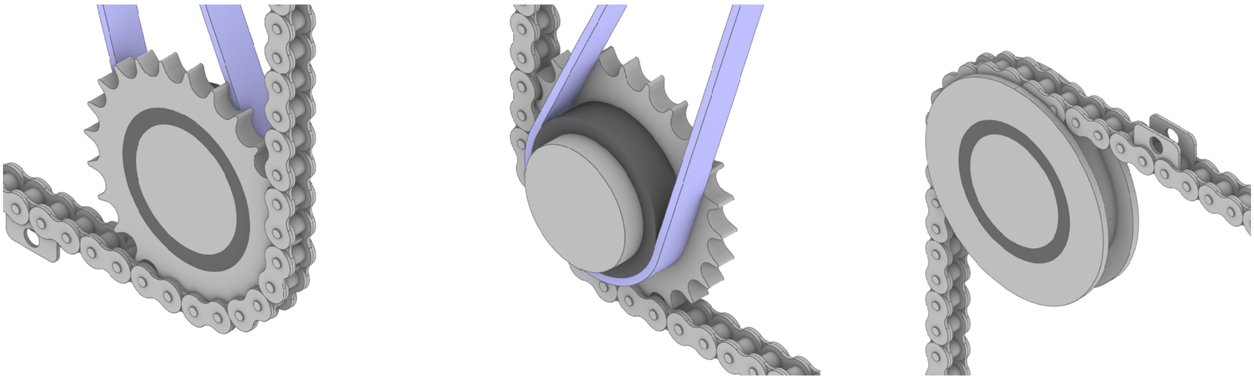


figure 48: sprocket (l + c) and chain sheave (own, 2023)

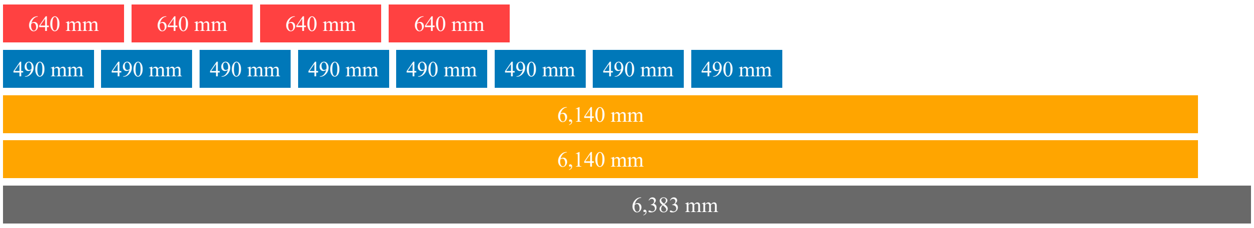


figure 49: required lengths of midfield column for a single system (own, 2023)

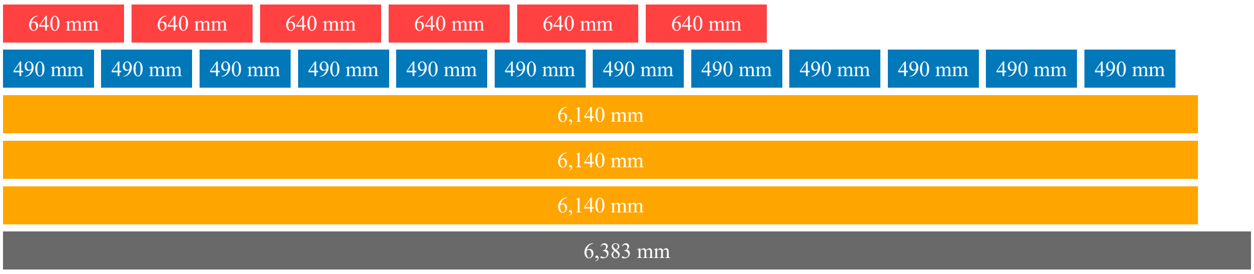


figure 50: required lengths of midfield column for a coupled system (own, 2023)

In bigger module configurations most of the bracing will have to be new, because demolished greenhouses do not have enough bracing to provide a lot of system structures with bracing. However, as the bracing and the crossbeam could be redesigned for the system, opposed to the bracing in modules that is reused as it is found in a greenhouse, a smart detail was designed. *Figure 51* shows how a crossbeam can be bolted to a bracing strip, so **only** the bracing strip has to be welded to the vertical column. This is an improvement to the standard practice where both the crossbeam **and** the bracing strip are welded to the a column.

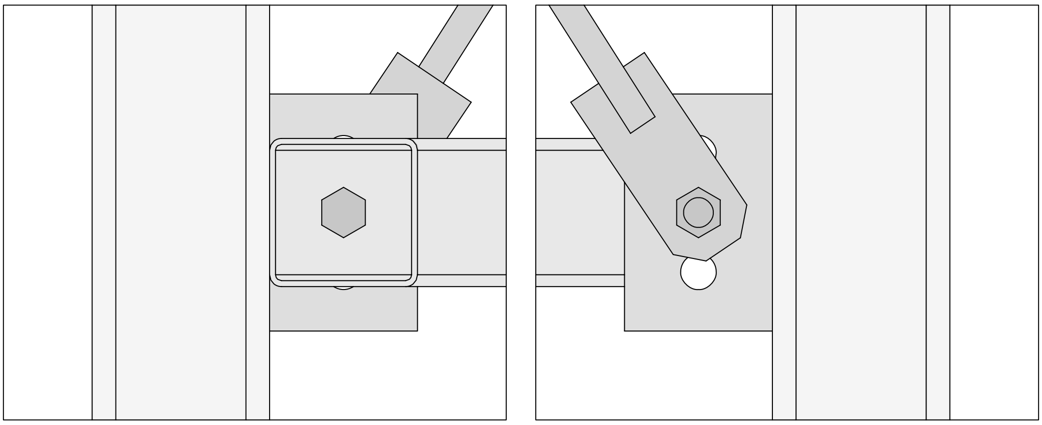


figure 51: detail of crossbeam and bracing strip with only one weld (own, 2023)

caps

To prevent moisture from getting into the columns rubber caps are designed that fit exactly in the 152x52 opening of the 160x60x4 columns, these caps are 20 mm wide, of which 10 mm is inside the column, and 10 mm on the outside. The caps on the feet also serve as shock dempers when growing systems are slided against each other. Including the caps, the total width of growing systems is calculated as: 10 (cap) + 640 (foot) + 160 (vertical) + 640 (foot) + 10 (cap) = 1,460 mm wide.

light

Artificial light is mounted between the vertical columns of the structure. Steel strips of 1,840 mm long are mounted at an angle so the light beam, when Philips GreenPower LED production modules (Philips, 2022) are fixed to the strips, falls precisely on the container surface. Why there are precisely nine lights is explained in p5 optimize c1 light. How the lights are incorporated into the structure of a coupled system is shown in *figure 52*, and how they relate to the resting positions of containers in *figure 53*. Lights mounted are as far above the containers to enable an as even as possible illumination over the width of containers.

irrigation

Irrigating a sliding system is a challenge; it requires an extendable hose that supplies irrigation water. It is confirmed withing VB that such hoses exist (Marcel van Leeuwen [VB], personal communication, January 22, 2023), however the precise design of it is left to follow-up research, and is addressed in p8 conclusion c2 discussion. However, the distribution of irrigation water from the supply hose onwards is designed; it uses a horizontal pipe that fits into the space between the vertical column and moving containers. Directly above the irrigation slot of containers, this pipe has a downward deflection to release water as close to the slot as possible without touching the container (*figure 52* and *figure 53*).

rails

The single and coupled systems can slide on a rail. This way workspace can be created only where it is needed, so all other space can be occupied by growing systems and not by unused workspace. The rails is cast in concrete beams that support the system lines, which in turn is embedded in the (soil) floor. The rails under a coupled system is shown in *figure 52* and *figure 53*.

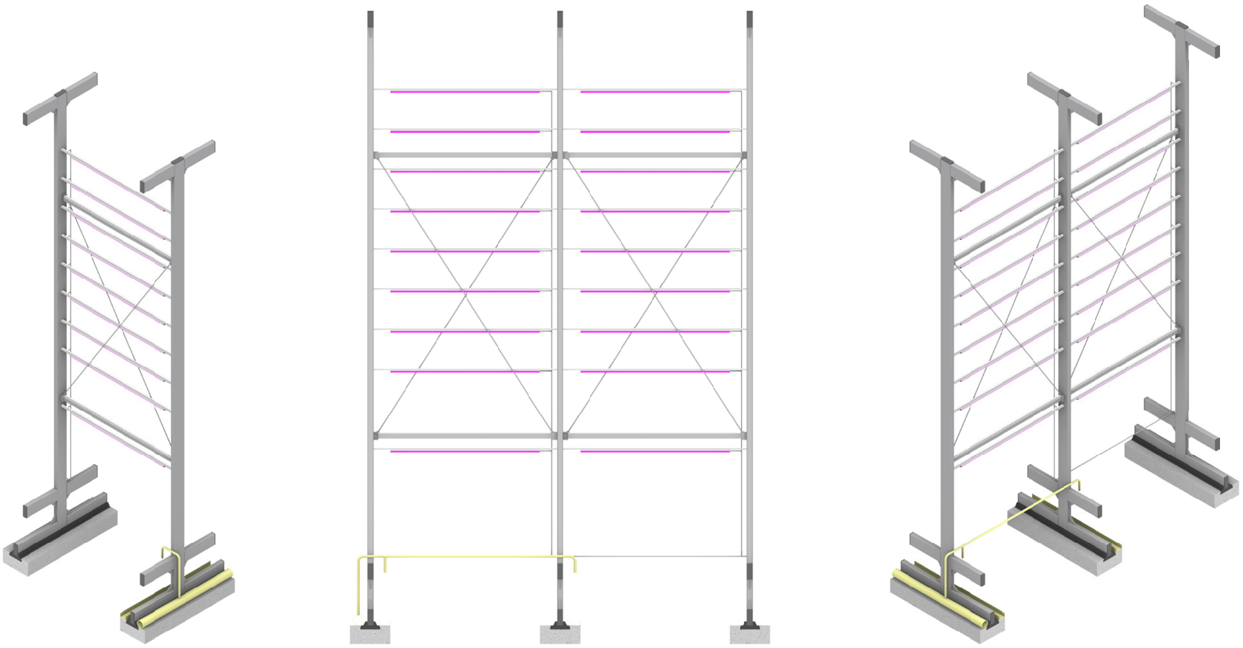


figure 52: structure, artificial light, irrigation, and rails (own, 2023)

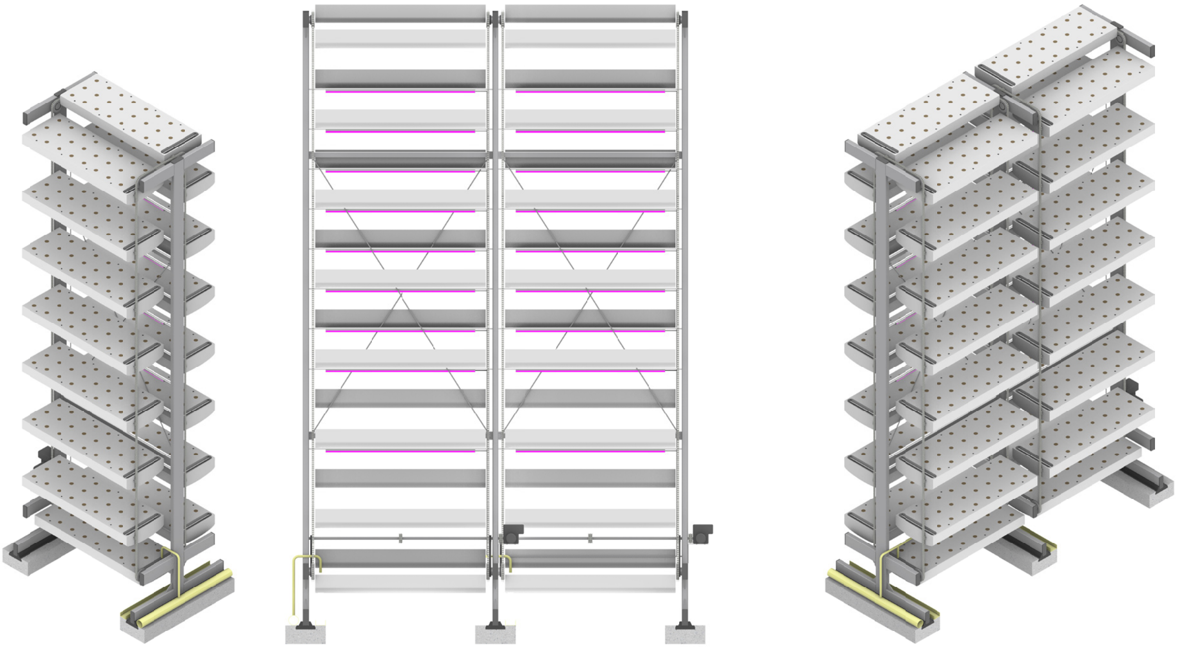


figure 53: structure, artificial light, irrigation, rails, drive, and containers (own, 2023)

more containers

Growers might want to grow more crops per system. The capacity of the system with sixteen containers spaced 800 mm (left in *figure 54*) can be increased by either adding 800 mm of vertical to the system and add two new containers space 800 mm apart (center in *figure 54*). Then you cannot reuse midfield columns, as the vertical now is 6,940 mm and midfield columns are onlyh 6,383 mm). Containers can also be spaced closer together (sixteen 720 mm apart, two 640 mm apart) (right in *figure 54*), but only be done when small crops like microgreens or cresses are cultivated, otherwise the top of the crops will touch the bottom of the container above it when the containers change from a vertical to a horizontal movement in the corners. Thus, to be able to reuse midfield columns (from MightyVine phase 3), and prevent crop damage, it is best to build a system with a capacity of sixteen containers spaced 800 mm apart.

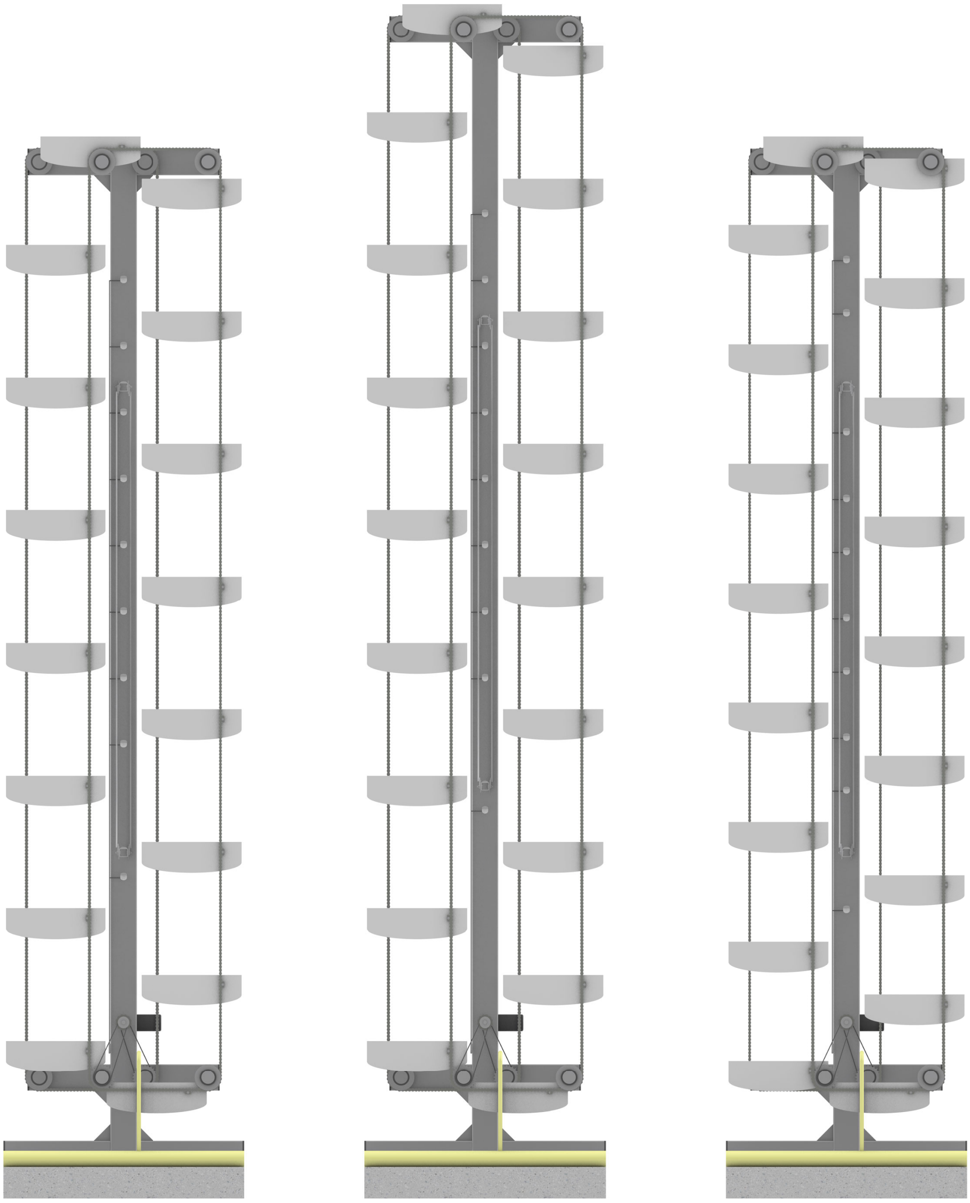


figure 54: more containers per system (own, 2023)

load

One container weighs 41.7 kg; the structure of the weight calculation is detailed in *table 2*. The calculation assumes a container with wet mosswool, with full-grown crops, that is being irrigated. In practice, this situation will not occur; in fact, mature crops are in containers without capillary mosswool cilinders. In addition, the amount of water in the container is overestimated. However, this calculation is the safest assumption to ensure structural conformity. The center midfield column in a coupled system carries containers and chains on both sides. The chains, create a load of 39.6 kg (total volume of 0.005 m^3, with a density of steel of 7,850 kg/m^3). This weight is used later on in the stress and buckling calculations. Each chain carries a load equal to the weight of eight containers (a chain carries half the load of the sixteen containers in a system, as the other half is carried by the chain that is connected to containers on the other side). The chosen chain is a Renold SD12B-1 roller chain, which according to European standards can withstand 28,900 Newton (N) in tensile strength. Eight containers weigh 333.76 kg (8 x 41.72 kg), or 3,338 N, which is below the chain's tensile strength (Renold, n.d.). Thus, the chain is proven to be strong enough.

table 2: container weight (own, 2023)

Part [-]	Material [-]	Volume [mm^3]	Volume [m^3]	Density [kg/m^3]	Weight [kg]
Tray support	Aluminium	225,000	0.0002	2,755	0.62
Capillary cillinder	Mosswool*	2,780,978	0.0028	1,250	3.48
Tray clod	Mosswool*	1,539,380	0.0015	1,250	1.92
Propogation trays	Polycarbonate	3,314,296	0.0033	1,200	3.98
NFT overflow bar	Polycarbonate	3,750	0.0000	1,200	0.00
NFT plate	Polycarbonate	2,475,000	0.0025	1,200	2.97
NFT cillinder support	Polycarbonate	4,712	0.0000	1,200	0.01
NFT irrigation slit	Polycarbonate	202,434	0.0002	7,850	1.59
Container belly	Polycarbonate	3,729,352	0.0037	2,755	10.27
Container front	Polycarbonate	519,296	0.0005	2,755	1.43
M10 bolts and nuts	Stainless steel	11,539	0.0000	2,755	0.03
Irrigation and nutrition**	Water	8,237,500	0.0082	997	8.21
24 crops***	Leaves and roots				7.20
Total					41.72

* *For the density of mosswool the density of moist dirt is assumed;*

** *For the volume of water three times that what fits on the NFT plate (2,471,250 mm^3) is assumed;*

*** *For the crop weight twenty-four full grown heads of lettuce of 300g is assumed.*

stress

The stress in a center midfield column of a coupled system is calculated by dividing the imposed force *F* by the cross-sectional area *A*. The cross-section of a RHS 160x60x4 column is retrieved from Dlubal (n.d.):

- F = 16 containers x 41.72 kg + 2 chains x 39.6 kg = 746.72 kg = 7,467 N
- A = 1,650 mm^2
- σ = 7,467 / 1,650 = 4.52 N/mm^2 < 235 N/mm^2 = OK

Because the stress per mm^2 is lower than the stress that a RHS 160x60x4 column steel can handle, the imposed load is acceptable and the structure can support it without failing. In fact, the difference is so great, only 1.92% of the compressive strength of S235 steel is used, that in theory much heavier and larger containers, or many more containers, could be used in the system.

buckling

The buckling number *n* is calculated by dividing the buckling load F_{cr} by the imposed load $F_{c;d}$, and must be greater than 5. Cross-sectional proporaties of a RHS 160x60x4 column are retrieved from Dlubal (n.d.):

- F_{cr} = $(\pi^2 \text{ x } E \text{ x } I_z) / l^2 = (\pi^2 \text{ x } 210{,}000 \text{ x } 1{,}060{,}000) / 5{,}520^2 = 72{,}102$ N
- $F_{c;d}$ = 7,467 N
- n = 72,102 N / 7,467 N = 9.65 > 5 = OK

The buckling number is greater than 5, so in terms of buckling, the structure is satisfactory. The buckling number, with a value of 9.65, is almost double as high as 5. This margin of 193% ensures that a growing system can be expanded by two extra containers (or, 800 mm in height) without becoming structurally unsufficient in terms of buckling. Also, the margin guarantees that the calculated column can support the weight of the two upper steel side arms (2 x 0.00106 m^3 x 7,850 kg/m^3 = 16.63 kg) and the sprockets and chain sheaves, which have been excluded from this calculation.

speed

Containers rotate so they all receive an even amount of natural light, and they are equally supplemented with artificial light. However, containers do not move constantly, they are hold stationary when the bottom containers is irrigated. The temporary immobilization of containers is advantageous because it ensures that artificial light can be ideally placed relative to the resting position of the containers in the system.

There is 800 mm of chain between the container suspension points, so in a system with sixteen containers, the total length is 12,800 mm. The intention is for containers to complete one rotation every hour. Thus, a distance of 12,800 mm must be traveled in 3,600 seconds. However, a three-minute period is assigned to irrigate containers, giving them time to drain the overflow. This means that sixteen three-minute intervals, totaling forty-eight minutes, are not available for rotation. For the speed at which containers move, this means traveling 12,800 mm in 720 seconds; or 17.8 mm per second (0.06 kilometers per hour). At this speed, workers do not risk getting suddenly stuck in the machines and damage limbs. A grower may choose to rotate containers twice an hour, this reduces the effect of (rapidly) changing weather conditions on the amount of natural light containers receive, and even prevents containers from receiving varying daylight levels. In that case, the irrigation period is halved to one-and-a-half minutes. So then the system must travel 25,600 mm (twice 12,800 mm) in 720 seconds, or, 35.6 mm per second (0.12 kilometers per hour). This speed still poses no risk to workers, but it is of course required that at all times an emergency stop button be present for workers to prevent unfortunate accidents.

When workers are working with crops, the rotation of a growing system is stopped for as long as necessary. After the workers have finished, the rotation will restart at the next interval, so that the containers will again move in sync with the adjacent containers, and reflective behaviour of the container belly works optimally.

p4

system

The research in each part is conducted to answer one or more sub-research questions, which will ultimately help answer the main research question. These sub research questions are answered by means of a certain product, identified in p1 intro c3 research. The results are discussed here.

In p4 system one sub research question has been answered, the fourth one. The question and the approach to finding an answer to it were:

4. Regarding the aspect "become high yielding": *"What are strong characteristics of existing vertical farm typologies and how can they be combined?"*. It is answered in p4 system by means of an analysis of vertical farm typologies, their floor space index, and desirable features **and** a design for a growing system that reuses a case study greenhouse's components.

This question is answered in c2 typologies. To provide a concise answer to this question, a summary of the conclusion of the typology analysis is given below:

Eight vertical farming typologies were studied: two-layer, standing, towering, riding, hanging, racking, sliding, and rotating. Not all typologies use the footprint of half a module equally efficiently. The typology that can provide the most cropping area on the 20.25 m^2 footprint is a sliding system, with a floor space index (FSI) of 444%. It can be that high because a sliding typology eliminates the need for constant workspace between all systems, in this typology, only workspace is created next to a system whose crops an employee wants to access. The rest of the systems remain adjacent to each other, allowing for much denser utilization of the footprint. Therefore, strong characteristic of existing vertical farm typologies is one: sliding.

The typologies were also categorized using eight sets of icons, with one icon in each set representing a positive characteristic (meaning it does contribute to the typology's sustainability, to the easy access of crops, to its longevity, or to its ease of use, etc.). The only typology that was assigned all eight positive icons was the rotating system; it is naturally lit, low-tech, manual, self-supporting, dynamic, accessible, modular, and can be made from reused components. In particular, the fact that this dynamic typology rotates crops towards the deck of a greenhouse, where it can receive daylight is a highly beneficial feature, because it reduces the artificial light requirement. Rotation also makes the crops move to the employee, rather than the other way around (with would require an aerial platform). This allows rotating systems to be placed closer together because only a human needs to move between them, not a large machine. Therefore, strong characteristic of existing vertical farming typologies two is: rotating.

The two characteristics are combined by designing a growing system in which containers rotate along chains (driven by reused ventilation window drive motors) in a system that is placed on rails embedded in concrete in the floor of a hybrid urban vertical farm. For the construction MightyVine phase 3 midfield columns are reused. This is possible, considering the toolbox of reclaimable components from p3 module c1 case study. Midfield columns are least likely to be reused because module configurations have a greater ratio of gable columns to midfield columns than the greenhouse their components originate from (they need to be small-scale to fit in urban environments). The design, which **combines** both the sliding and rotating characteristic, is built up, explained and visualized in c3 design.

part five

optimize

p5

optimize

in this part

In p5 optimize the optimal module configuration layout is researched by studying how as many systems can fit in a configuration that reuses as many reclaimed components as possible. To this end, it must be determined how far apart the systems should be, as this has the greatest affect on how many systems will fit in a module configuration. Therefore, first, c1 light studies how far apart systems should be to maximize daylighting/minimize artificial lighting per m^2 footprint. Second, c2 fsi examines what configurations can fit the most systems (using the spacing from the previous chapter) and have to the highest floor space index (FSI). Third, in c3 columns it is studied which of those configurations reuses the most midfield columns in the construction of both modules ***and*** *systems. The configuration that scores highest is the one that has the highest reuse percentage of all possible configurations* ***with*** *a high FSI. The carbon footprint of that configuration will be compared to the carbon footprint of the case study greenhouse in p6 compare.*

To gain insight into the resources that crops need, especially their photosynthetic photon flux density (PPFD) requirement, a visit was made to Koppert Cress, Monster, the Netherlands. This company cultivates cress for celebrity restaurants around the world. The person spoken to is head of the R&D department at Koppert Kress, Division Q, Bart van Meurs. The visit is refered to as *(van Meurs, B. [Koppert Cress], personal communication, January 10, 2023)*.

c1 light

c2 fsi

c3 columns

in this chapter

To make the best use of the system designed to use daylight and reduce the need for artificial lighting, it is necessary to determine how the system should be set up. There are two criteria for this, the resting position of containers in growing systems, and the distance between system units. In this chapter it is studied what the parameters are for both criteria in order to use as much daylight per m^2 footprint.

synchronization

The containers in a system rotate, but as each container at the bottom is irrigated for a while, the containers are stationary most of the time. It is expected that the position of containers in that idle position relative to containers in adjacent systems lines has much influence on the amount of daylight that can reach the growing surfaces. Two configurations are simulated: 1) *in sync*, where containers move directly next to containers from adjacent system units when going up and down, and 2) *out of syn*c, where containers move above/below containers from adjacent system units when going up and down. The simulation is performed on the growing surfaces of the middle system units in two system lines of five system units. This is most container-dense configuration that can occur in a hybrid urban vertical farm; any other configuration will generate more favorable simulation results, justifying this approach. *Figure 55* and *figure 56* show the difference between in sync and out of sync configurations. The gray geometries are context in the simulations, on the orange geometries the total radiation is simulated in the simulations.

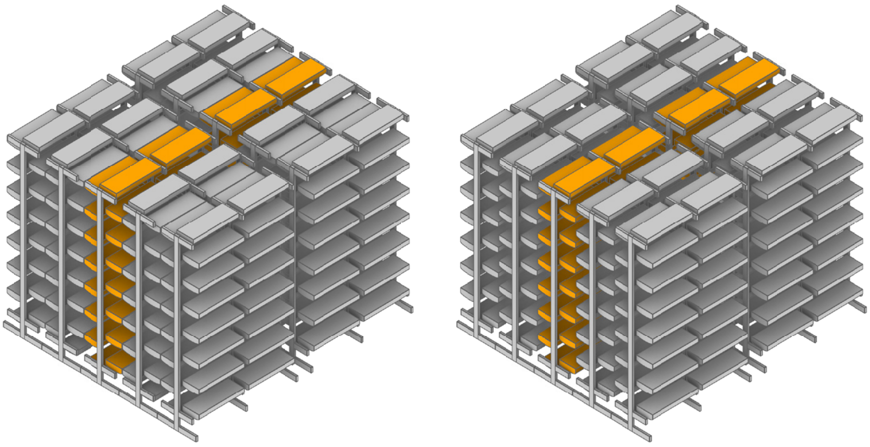


figure 55: axonometrics of an in sync (l) and out of sync (r) system configuration (own, 2023)

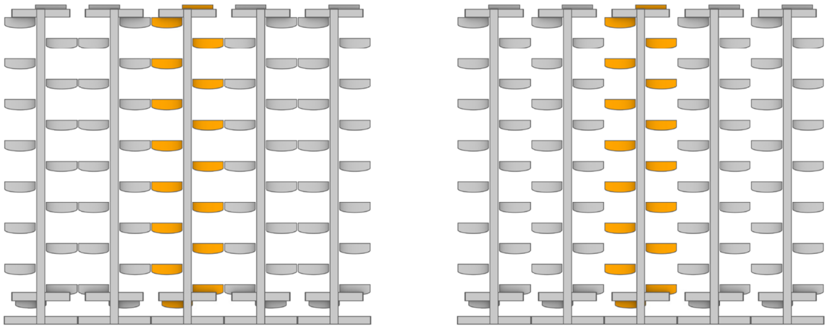


figure 56: elevations of an in sync (l) and out of sync (r) system configuration (own, 2023)

script

Figure 55 and *figure 56* show that orange geometries exist of more surfaces than only growing surfaces. Because a Grasshopper/Ladybug script is used for the simulations, it can be optimized to simulate only radiation for the growing surfaces, otherwise the low radiation on the other surfaces is included in the calculation of the average radiation value on the growing surfaces. This is illustrated in *figure 57*; the simulation calculating all surfaces of the container (l) results in an average radiation of 23.13 kWh/m^2, the simulation calculating only the growth area results in an average radiation (r) results in an average radiation of 49.36 kwh/m^2. The difference is more than half and thus significant to remove from the calculation.

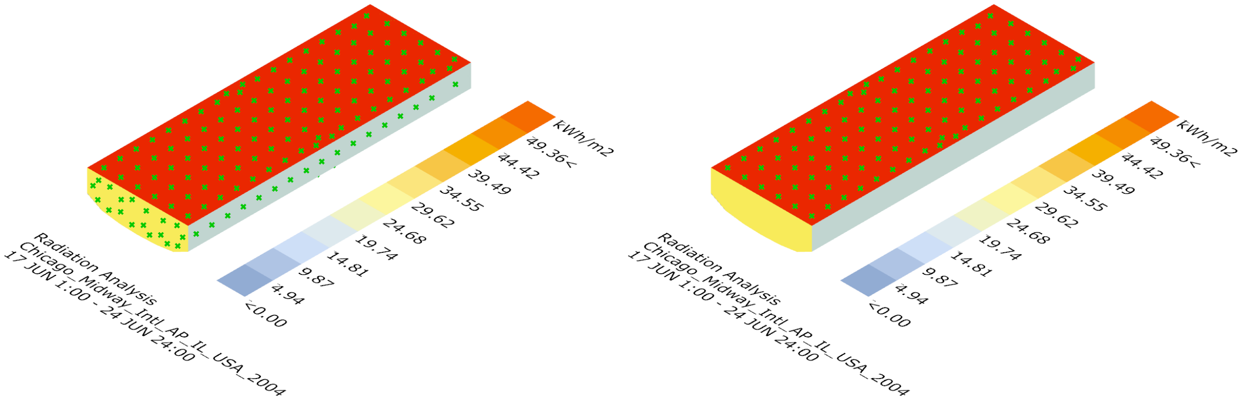


figure 57: output of an unoptimized (l) and an optimized script (r) (own, 2023)

results (synchronization)

Simulations are run over a one-year period, using an EnergyPlus Weather File (.epw) from a Chicago site nearby the case study. The simulations for the in sync and out of sync scenarios result in average radiances of 66.5 kWh/y.m^2 and 62.6 kWh/y.m^2 per year, respectively. Thus, despite a small difference, it is concluded that an in sync rotation utilizes more daylight, and can save more on artificial light. Furthermore, the more space between system units, the greater the effect will be. Simulation results are shown in *figure 58*.

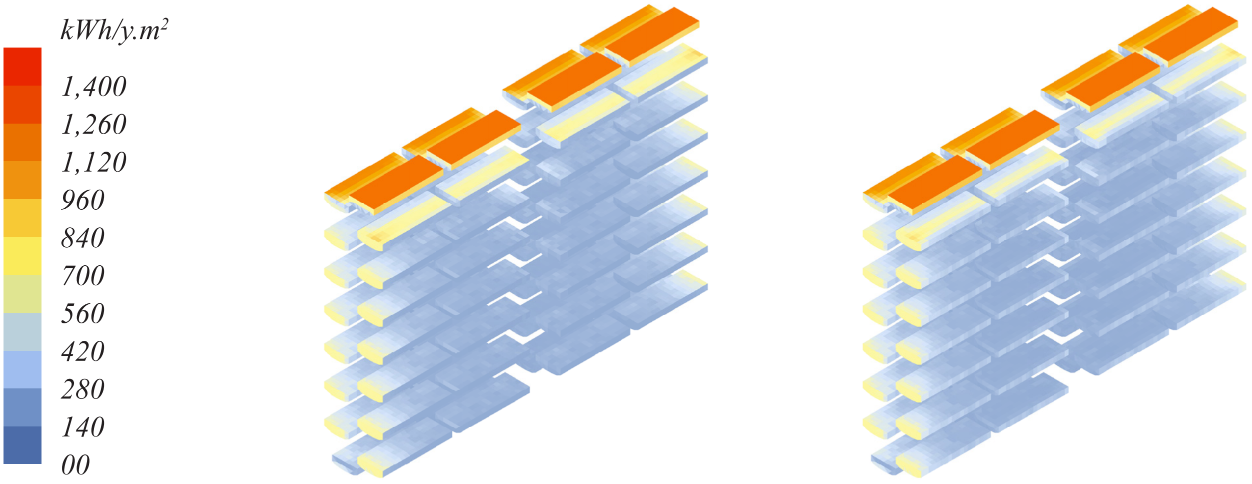


figure 58: simulation results of an in sync (l) and out of sync (r) configuration

spacing

Having determined that system units should rotate in sync, the spacing between system units to allow maximum daylight can be determined. To do this, three configurations are simulated, consisting of two back-to-back system lines of five system units. This scenario can occur when two or more modules are linked in the bay direction. In practice, there is some space reserved between the two system lines for piping, which will be defined in p5 optimize c2 fsi, for now it is estimated between 500 and 1,000 mm, so the minimum of 500 mm is assumed. That assumption justifies the results of the simulations; extra space between system lines will result in more favorable radiation averages than this simulation. This is the most container-tight scenario that can occur in hybrid urban vertical farms. By simulating that scenario, more favorable scenarios will also satisfy with the artificial light requirements that will result from these siulations. Three configurations are computed, 1) system units are spaced 1,460 mm apart, equal to the width of a growing system, named *full* spacing, 2) system units are spaced 730 mm apart, equal to half the width of a growing system, named *half* spacing, and 3) system units are side by side without spacing, named *zero* spacing. The three configurations of the scenario are illustrated in *figure 58*.

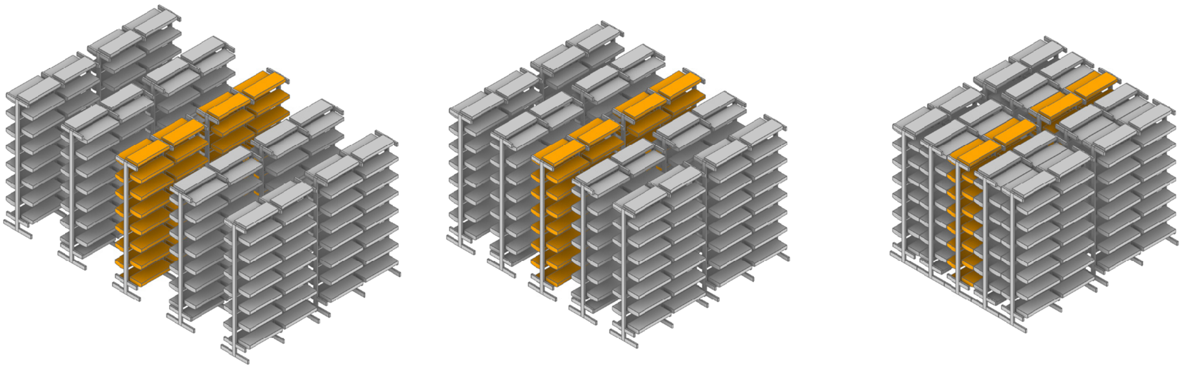


figure 59: axonometrics of a full (l), half (c), and zero (r) configuration (own, 2023)

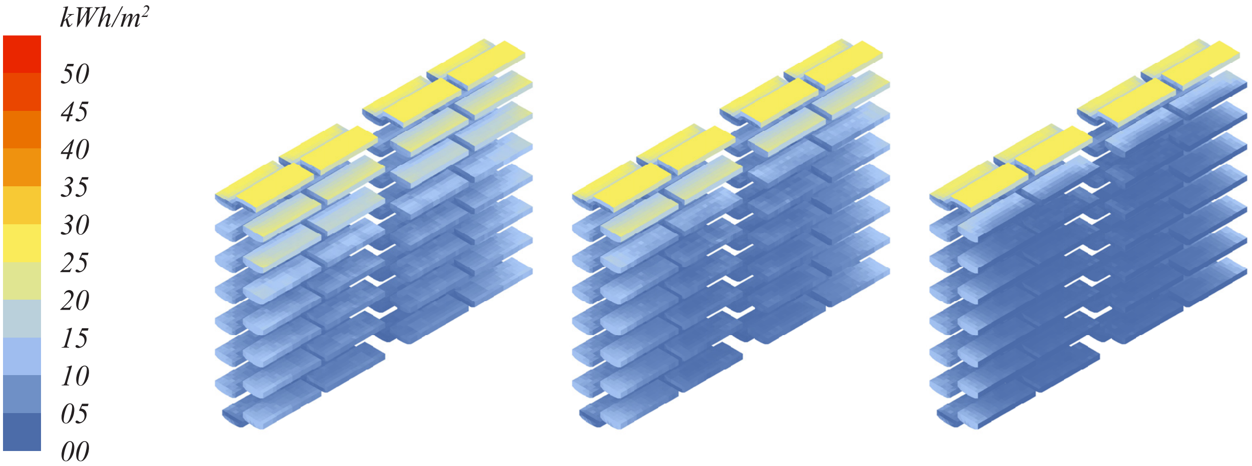
approach

Again, an .epw is used. Four simulations are run for each configuration. For a balanced annual view, the weeks around June 21 (summer), December 21 (winter), and March 21 (spring; equal to September 21, fall) are simulated. A week is used to avoid the simulation being affected by a sporadic cloudy day. In order to determine the benefit of the hybrid urban vertical farm philosophy on a yearly basis, an annual simulation is run as well. The simulations output the sum of radiation on the growth surfaces of the trays, from which an average can be calculated, which can be converted to a photosynthetic photon flux density (PPFD) in μmol/s.m^2 by dividing by the simulation period. Next, a transmission factor of the greenhouse deck must be applied, as the simulation is run as if the configurations were in the open air. Then, the amount of daylight hitting the growing surfaces can be determined, and thus the photon current required of artificial lighting.

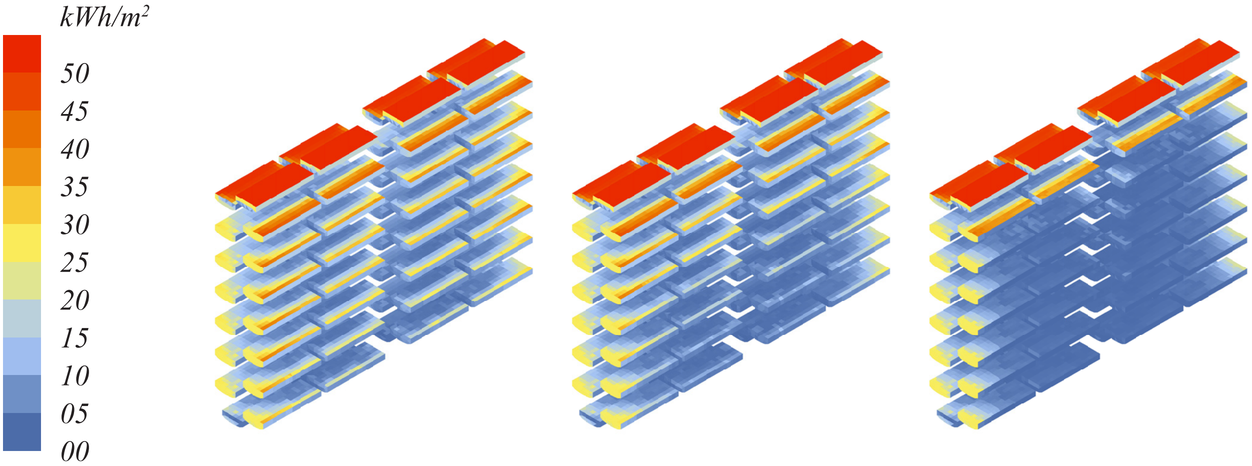
results (spacing)

The simulation results are shown in *figure 60* and *figure 61* on the next page, along with a standardized legend that indicates the amount of kWh/m^2 that hits the growth surface during the simulation period. The maximum radiance for a weekly calculation occurs for the *full* configuration in June, that value nears to 50 kWh/w.m^2, therefore the legend scale for weekly calculations is calibrated to 50 kWh/w.m^2.

For annual calculations, the maximum is also for the *full* configuration (1,369 kWh/y.m^2), so its legend is calibrated at 1,400 kWh/y.m^2. With calibrated legends, the difference between the configurations can be seen at a glance. It is clear that in June most daylight falls on the growing surfaces, in March less, and in winter almost none, which is caused by varying sun intensity throughout the seasons. The upper growing surfaces receive the most light, the lower growing surfaces the least. Annually, the full configuration gets the most daylight.



full, March *half, March* *zero, March*

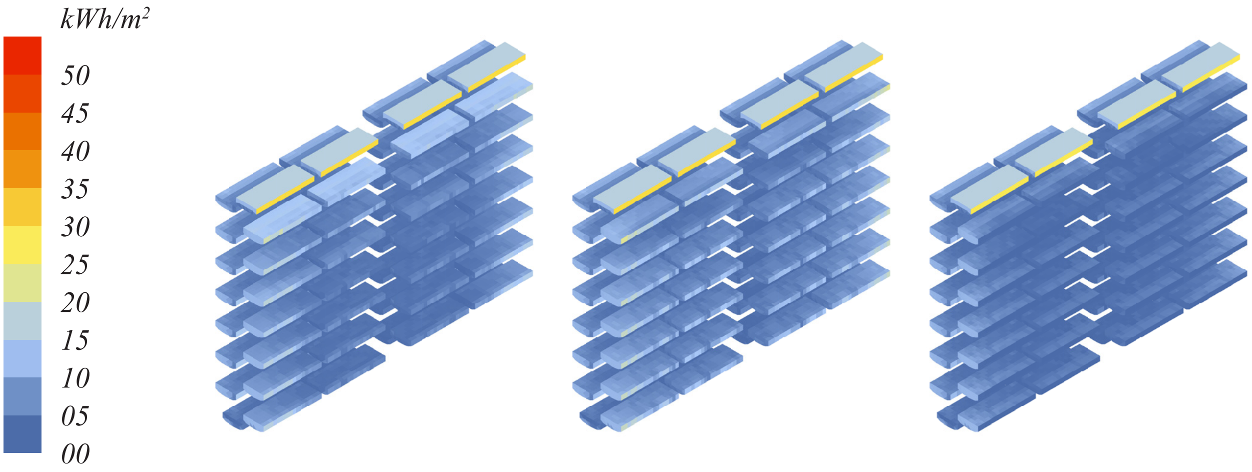


full, June *half, June* *zero, June*

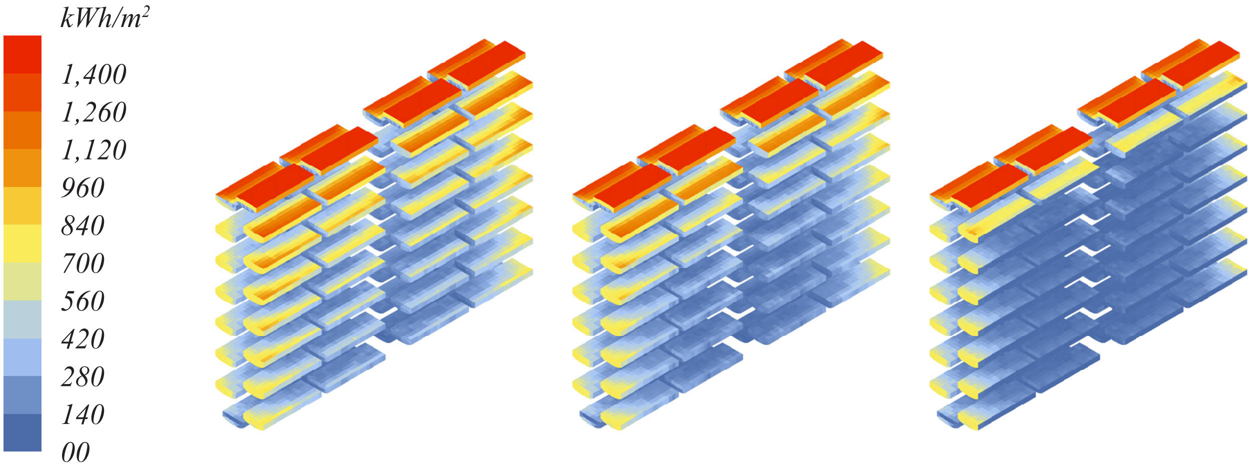
figure 60: simulation results of a full (l), half (c), and zero (r) configuration (1/2) (own, 2023)

data conversion

After running each simulation, the Grasshopper/Ladybug script outputs a list of radiation data for all test points, which has been optimized to output the data for test points on the growing surfaces only. That data is converted to a photosynthetic photon flux density (PPFD), so the amount of artificial lighting that is required to supplements daylight in each season can be caclulated. For this the following steps are taken:



full, December half, December zero, December



full, year half, year zero, year

figure 61: simulation results of a full (l), half (c), and zero (r) configuration (2/2) (own, 2023)

- Copy and paste the radiation data in kWh/m^2 to Microsoft Excel;
- Calculate the average of all data in kWh/m^2;
- Convert kWh/m^2 to Wh/m^2 by multiplying by 1,000;
- Convert Wh/m^2 to W/m^2 by dividing by the number of hours over which the simulation was run (168 hours for a week simulation, 8,760 hours for a year simulation);
- Convert W/m^2 to µmol/s.m² (PPFD) by multiplying by 2.06.

Often a factor of 4.57 is used to convert W/m^2 to µmol/s.m², but as only 45% of radiation is PAR (400-700 nanometers), 2.06 is used here (van Iersel, 2017). The conversion results are presented in *table 3*. The simulation period [Period] and configuration [Conf.] are given first. The radiation in kWh/m^2 is given [Av. rad. 1], calculated by averaging the radiance sum of all test points.

Using the simulation duration [Hours], the radiation in W/m^2 [Av. rad. 2] can be determined, which can be converted to the naturally received photon flux [PPFD nat.] using the factor of 2.06. As crops require 173.6 µmol/s.m^2 [PPFD tot.] (van Meurs, B. [Koppert Cress], personal communication, January 10, 2023), the deficit that must be supplemented artificially is determined by subtracting [PPFD nat.] from [PPFD. tot.] in [PPFD art.]. Finally, the savings on artificial light, by dividing the [PPFD nat.] by [PPDF tot.] is given as a percentage in the last column [Energy savings].

table 3: radiation conversion results (own, 2023)

Period	Conf.	Coupled systems [#]	Energy savings [%]	Foot print efficiency [%]	(Energy savings/m^2 growing surface)/m^2 footprint [%]
March	Full	10	51%	56%	28%
March	Half	12	42%	67%	28%
March	Zero	18	30%	100%	30%
June	Full	10	96%	56%	54%
June	Half	12	84%	67%	56%
June	Zero	18	63%	100%	63%
December	Full	10	24%	56%	14%
December	Half	12	24%	67%	16%
December	Zero	18	17%	100%	17%
Year	Full	10	53%	56%	30%
Year	Half	12	45%	67%	30%
Year	Zero	18	34%	100%	34%

conclusion (spacing)

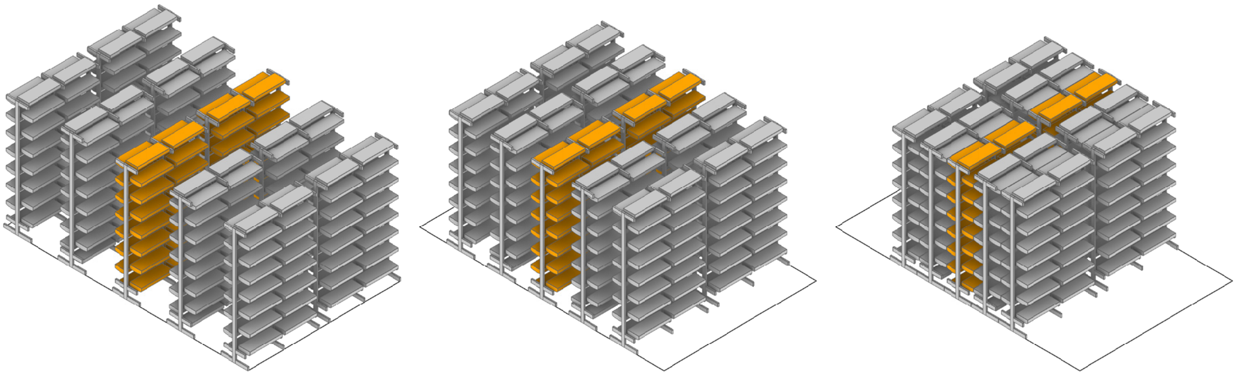
Table 3 shows that the savings on artificial lighting for a *full* configuration are higher than for a *half* configuration, and for a *half* configuration the savings are higher than for a *zero* configuration. This is true not only for week simulations, but also on an annual basis. Interestingly, a full configuration in June can provide 96% of PPFD with daylight; almost all of it. On an annual basis, this configuration can provide more than half of the total PPFD (53%) naturally, which is a great saving on artificial light. Logically, less can be saved on artificial light in March and December because the naturally provided PPFD is low.

space utlilization

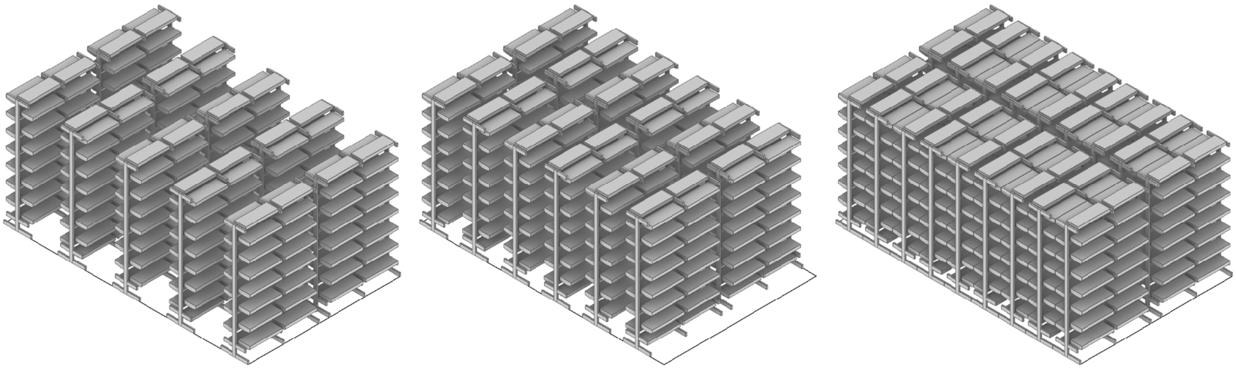
Considering daylight utilization only, a zero configuration does not seem like a good option for artificial light savings. That is because the light optimization so far considered artificial light savings only. The fact that the cultivation area of a full configuration cultivation does not use the available floor area efficiently has so far been disregarded. However, if a small cultivation area saves lots of energy per m^2 footprint, then the overall energy savings may be lower than if a big cultivation area saves less energy per m^2 footprint. Somewhere there is a balance between energy savings and footprint utilization, and that is sought here.

Figure 62 visualizes the space usage of the configurations. The footprint occupied by a full configuration is the value to which the other configurations are compared; it appears as a frame in all images. The top row shows how the footprint of configurations compare. A coupled system has a footprint 6.0 m^2, but the footprint of space between systems differs per configuration. A full configuration occupies 108 m^2, a half configuration 84 m^2, and a zero configuration 60 m^2. The middle row shows how each configuration can optimally utilize the 108 m^2. The full configuration cannot fit more system units on it due to its 1,460 mm spacing, so it remains at two system lines of five system units, totalling 10 coupled systems.

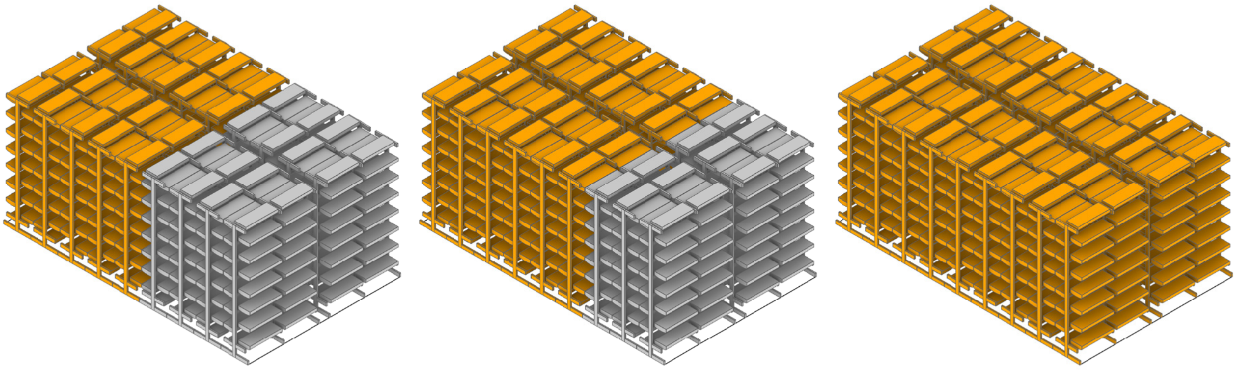
The half configuration can fit one more coupled systems on each system line, as it requires less space between its systems, it now totals 12 coupled. The zero configuration can fit four more coupled systems on each system line, totalling 18 coupled systems. The zero configuration thus theoretically has the greatest space utilization, and is taken as the benchmark for comparison of space utilization efficiency.



full footprint (108/108 m^2) *half footprint (84/108 m^2)* *zero footprint (60/108 m^2)*



full footprint utilization (10/18) *half footprint utilization 12/18)* *zero footprint utilization (18/18)*



full footprint efficiency (56%) *half footprint efficiency (67%)* *zero footprint efficiency (100%)*

figure 62: footprint, utilization, and efficiency a full (l), half (c), and zero (r) configuration (own, 2023)

This lead to footprint efficiencies of 56% for a *full* (10/18), 67% for a *half* (12/18), and 100% for a *zero* configuration (18/18), respectively. In *table 4*, these are multiplied by the energy savings from *table 3* to calculate an index that indicates the combined potential of energy savings and footprint utilization. The configuration with the highest combined index (*Energy savings per m^2 growing surface/m^2 footprint*) is best in terms of total energy savings in any space. **This is the zero configuration, with an index of 34%. Thus, the conclusion, further optimizations and calculations should be for an *in sync zero* configuration.**

table 4: combined energy savings and footprint efficiency results (own, 2023)

Period	Conf.	Coupled systems	Energy savings	Foot print efficiency	(Energy savings/m^2 growing surface)/m^2 footprint
		[#]	[%]	[%]	[%]
March	Full	10	51%	28%	14%
March	Half	12	42%	33%	14%
March	Zero	18	30%	50%	15%
June	Full	10	96%	28%	27%
June	Half	12	84%	33%	28%
June	Zero	18	63%	50%	31%
December	Full	10	24%	28%	7%
December	Half	12	24%	33%	8%
December	Zero	18	17%	50%	9%
Year	Full	10	53%	28%	15%
Year	Half	12	45%	33%	15%
Year	Zero	18	34%	50%	17%

Philips lights

Now that the optimal arrangement of the system has been figured out, it is important to determine what type of artificial light is needed to supplement the PPFD requirement that daylight cannot meet. In the previous light and space optimizations, it is determined that it is best to rotate system units in sync and place them side by side in a zero configuration. Foregoing optimization lead to the conclusion that on an annual basis 34% artificial light can be saved, and an average of 115.35 µmol/s.m² must still be supplemented.

seasonal differences

The artificial light output should be tuned to the time when there is the least amount of daylight available, which is in the December week simulation. During that week, 17% can be saved on artificial light, there is still 143.73 µmol/s.m² left to be supplemented. Per single system, in which sixteen containers with a growth surface of 1.04 m^2 rotate, 16.69 m^2 must be supplied with artificial light. Thus, 16.69 m^2 x 143.73 µmol/s.m² = 2,398.57 µmol/s must be emitted. In its range for multilayer cultivation, Philips offers the GreenPower LED production module, which has a variant for strawberry cultivation with an output of 280 µmol/s.

With 2,398.57 / 280 = 8.56 ≈ 9 lights, the total light sum can be provided in winter by providing 83% of the PPFD requirement with artificial light, and 17% with daylight. The GreenPower LED production module has 36,000 burning hours (Philips, 2022). To get the artificial light onto the crops as efficiently as possible, these are mounted at an angle during construction of growing systems, as explained and visible in the design in p4 system c2 design. Other lighting concepts are soon discussed too, at the end of this chapter.

In March (and September), 30% of PPFD requirements can be met with daylight, so 122.12 µmol/s.m² must be supplemented. For sixteen containers, this is 2,038.18 µmol/s, which is 85.0% compared to December.

This can be met in two ways; either with eight artificial light fixtures burning (one of nine can be off); or by running the nine artificial light fixtures at 85.0% power. Dimming is better for even illumination of crops. In June, 63% of PPFD requirements can be met with daylight, so 64.25 μmol/s.m² must be supplemented. For sixteen containers, this is 1,072.33 μmol/s, which is 44.7% compared to December. This can be met in two ways; either with four burning artificial light fixtures (five of nine can be off); or by running the nine artificial light fixtures at 44.7% power. Again, dimming is better for even illumination of crops.

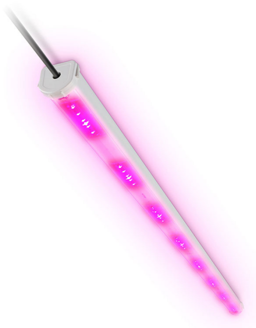


figure 63: Philips GreenPower LED production module (Philips, 2022).

considered: one light per layer

In a system, lights are placed as high as possible above containers at all rest positions. This way artificial light illuminates them as evenly as possible, both at individual rest positions (by mounting at an angle), and across all rest positions (by having lights everywhere). Nevertheless, crops close the light will receive more PPFD than crops located further from the light. But, as containers move in sync with containers of adjacent growing sytems, crops are also illuminated by the lights of an adjacent growing system. Thus, for every two containers moving in sync, two lights illuminate the crops. The overlap of artificial light is intended to provide uniform illumination; illustrated on the left in *figure 64*. **Important:** as the containers rotate, the crops that are furthest from the lights on the way up are closest to the lights on the way down; thus, artificial light is even better distributed to the crops as a direct result of the rotation.

considered: two lights every other layer

The illustration in the middle of *figure 64* shows how containers could be illuminated by two lights every other rest position, by adding one extra light on *one side* of each growing system every other rest position. In the example section in which nine containers are illuminated, eighteen lights are required to do this, equal to the amount of lights chosen lighting concept. However, in rotation containers now switch between brightly illumintated (high PPFD) and dark resting positions. As a result, crops cannot engage in photosynthesis for long periods of time, which slows down their development. In addition, now two lights illuminate a small area, thus PPFD is much higher than needed to supplement daylight. The illuminated growing surfaces at rest positions are now greatly overexposed (the overlap is colored dark purple in *figure 64*).

considered: two lights per layer

The illustration on the right of *figure 64* shows how the problems that occur when using two lights every other layer can be solved by adding extra lights on *both sides* of **each** growing system at **every** rest position.

This would allow plants to persistently photosynthesize. However, now thirty-six lights are needed for eighteen containers, a doubling of the previous lighting concepts. It is arguable that a lighting concept with lights on both sides of each container will provide crops with a higher PPFD to make them grow faster, but that is not the purpose of a hybrid urban vertical farm. Artificial light is only used to compensate for the lack of natural PPFD. So when more lamps are added, each lamp has to burn at a lower intensity, essentially not making good use of the purchased lamps and the stored energy that went into their manufacture (the lights in the lighting concept on the right side of *figure 64* emit the least intense light; colored light pink).

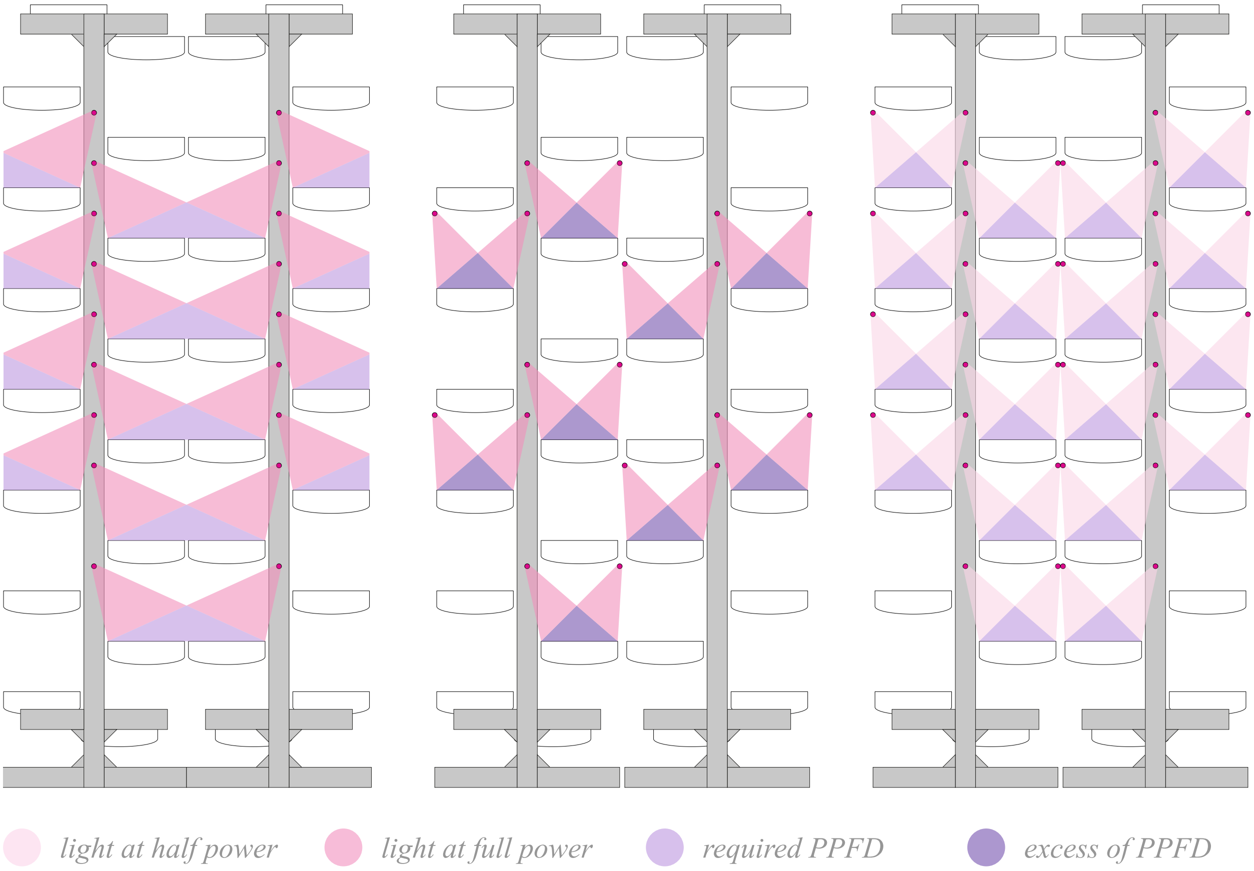


figure 64: chosen (l) and considered (c + r) lighting concepts (own, 2023)

disadvantages

Besides the aforementioned disadvantages (switching between lit and dark rest positions, or underutilization of lights), there are some more: first, lights mounted on the side of growing systems get in the way when workers need to access containers. Second, cables will run from the sides of a growing system to the power supply near the middle of the growing system, with the risk of getting caught, jammed, and/or broken. Third, lights on the outside of growing systems require a construction to be mounted to. That construction would have to be as thin as possible, to minimize obstruction of natural light. However, thin constructions are fragile, risking damaging the construction and the lights when growing systems are pushed together when sliding them on system lines. Taking all the disadvantages of the lighting concepts considered together, the reasoned choice was made to perform further optimizations and calculations with a lighting concept in which **nine dimmable artificial lights per sixteen containers** in growing systems are installed.

vertical farms

If a lighting concept had to be designed for a traditional vertical farm, three lights per layer would have been the best without question. But in that situation daylight utilization is not a factor either; then it would be all about the addition of artificial light, and not about saving energy through daylight maximization.

The research conducted in this chapter has been incorporated in the design of a hybrid urban vertical farm. Now, at its conclusion, references are made to the chapters in which the features identified as important in this chapter have been incorporated into the design.

- The optimization to the spacing of growing systems is used in the next optimization, which looks at how to fit as many systems in a configuration as possible (p5 optimize c2 fsi).

in this chapter

Some configurations lend themselves better to accommodate many growing systems close together on a small footprint. Therefore, the optimal layouts of sixteen configurations are studied to determine which features a configuration should have to get as much growing surface area per footprint as possible, or, in other words, which has the highest floor area index (FSI). The layouts are tied to conditions for walking space around and working space between systems. These conditions and the results of the sixteen layouts are discussed in this chapter.

approach

Sixteen module configurations plans are optimized, ranging from one to four trellises long, and one to four bays deep. In plans, included in appendix 5 the modules are drawn as red rectangles. In small configurations like these, only one row of midfield bracing is needed from sidewall to sidewall, as previously explained in p3 module c2 design. The midfield bracing is drawn as a blue cross. Here, shorter *midfield brace system lines* are used. When configurations of more than four bays deep are built, the optimized configurations can be copied so the space use efficiency will not change. Together with the columns of the structure, the bracing defines the free space where system lines can slide without running into the construction. In that free space single and coupled systems are drawn on system lines. When the use of single and coupled systems leads to an equal cultivation surface, the choice was made to use coupled systems in order to save on the number of columns needed for the construction of systems and the number of motors needed.

conditions

One system occupies a space of 1,460 mm (width, in the trellis direction) by 4,250 mm (lenght, in the bay direction). There are four principles for the space around those systems (illustrated in *figure 65*):

1. There is at least 1,500 mm of space between system lines for workers and equipment to pass each other, this is called *walkspace*;
2. There is at least 1,500 mm of unoccupied rails in each system line so workers can create sufficient workspace by sliding other systems into the unoccupied space, this is called *workspace*;
3. There is at least 1,500 mm of space between one sidewall and a system line that is not adjacent to an endwall, so workers and equipment can move along system lines. This is called *sidewall space*;
4. There is at least 1,500 mm of space between midfield bracing and the entrance side of a system, because workes and equipment cannot move through the bracing but must move around it.

In all cases, the 1,500 mm is assumed wide enough for transportation of workers, equipment, and space for any technical installations to and from the systems.

system line length

Because the growing system is designed with human comfort in mind, it is inconvenient for an employee to slide dozens of systems away to access one growing. Thus, it was decided to put a maximum of eleven systems per system line. Because growing systems slide on a rails, which takes away friction, pushing away a few systems at a time is doable. In contrast, if growing systems were actually to be put on system lines as long as the number of trellises in a module configuration allows, an employee could have to push away over a dozen systems, which is very difficult due to the accumulated mass, even when the rails remove friction.

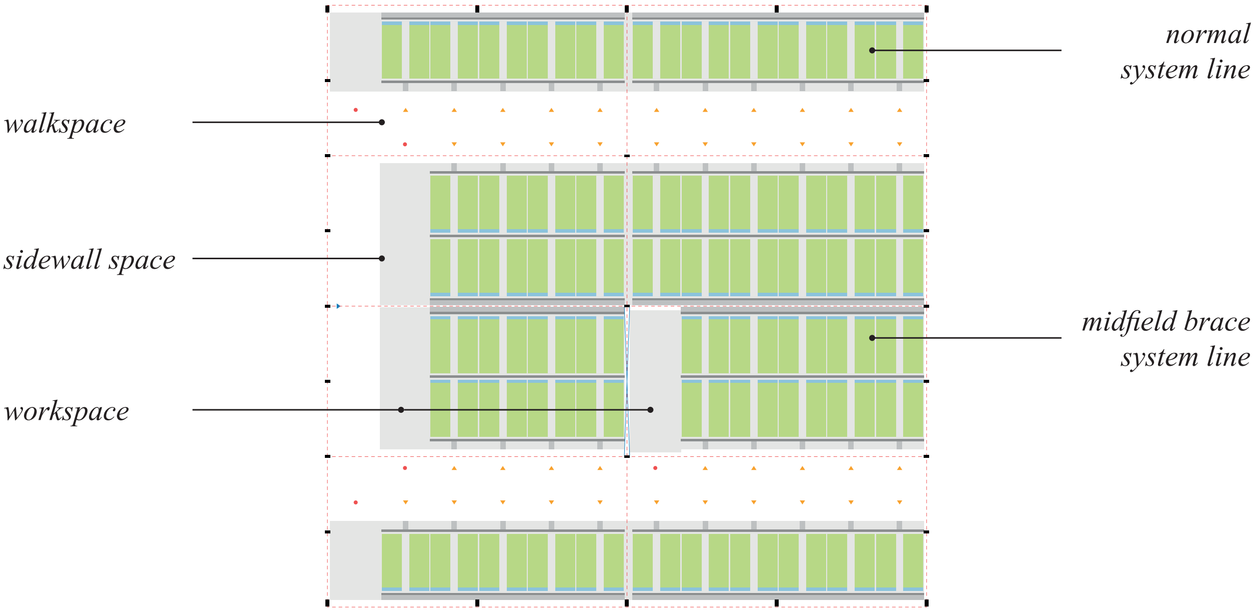


figure 65: module configuration plans conditions terminology (own, 2023)

configurations

These sixteen studies module configuration plans are included in appendix 5, where each configuration is named xT-xB (*x* being a variable *amount, T* meaning *trellises, B* meaning *bays*).

results

Table 5 shows the space use effiency for the sixteen configurations, ranked by number of trellises. The first column [Modules] says how many modules are in a configuration, [Configuration] then gives the name which explains how much of those modules are used in the trellis and bay direction. By multiplying the number of modules by their footprint (9,000 by 4,500 mm) the [Footprint] is calculated which is used to calculated how much could be grown on the footprint of the configuration if it were used for open-field cultivation [One layer]. However, these are all hybrid urban vertical farms, in which a multitude of systems in which 16 (single system) or 32 (coupled system) rotate; how many times there are 16 containers rotating in the plan is given in [# 16 containers]. As 24 crops can be grown in each container, it can now be calculated how many crops can grow in the hybrid urban vertical farm in [Multilayer]. By dividing [Multilayer] by [One layer], essentially dividing the growing surface by the footprint, the efficiency of each configuration is calculated in [FSI]. At last, it is proven that the walkspace, sidewall space, and workspace as required by the conditions set up earlier are respected in each of the plans.

Since there must be walking space around a midfield brace, in configurations of multiple trellises and only one bay, no more than five single systems can be placed. If more are placed in the other trellises they will not be accessible, hence the low efficiencies for configurations with multiple trellises and one bay. The plans show that a configuration of one bay deep uses around 50% of the depth of the configuration for systems, configurations of two and four bays deep (**note: an even number of bays**) use about 75%, of the available depth, and configurations of three bays deep use 67%. This is reflected in the FSI results; any configuration with an even number of bays is more efficient than any other configuration with that amount of trellises.

conclusion

Basis on this optimization study, it is not recommended to build multiple trellises together with only one bay, because the trellises are not accessible after the first one. However, it is advisable to connect **as many trellises** together as the location allows, to minimize the relative amount of *sidewall space*. It is then best to link an **even number of bays** to get the relative amount of walkspace as close to 25% as possible. In configurations built from components other than the MightyVine phase 3 components, it is still recommended to build growing systems as high as possible. For a 4T4B, the FSI when using growing systems with 14, 16, 18 and 20 containers per system is 257%, 294%, 331% and 367%, respectively. Every extra layer (two containers) adds 37 percentage point to the FSI, which is very significant.

table 5: optimized module configuration plans FSI results (own, 2023)

Modules	Configuration	Footprint	One layer	16 containers	Multilayer	FSI	Walkspace	Sidewall space	Workspace
[-]	[-]	[m^2]	[#]	[#]	[#]	[%]	[mm]	[mm]	[mm]
1	01T-01B	40.50	1,013	5	1,920	190%	1,710	-	1,540
2	01T-02B	81.00	2,025	15	5,760	284%	1,960	-	1,540
3	01T-03B	121.50	3,038	20	7,680	253%	4,560	-	1,540
4	01T-04B	162.00	4,050	30	11,520	284%	2,405	1,500	1,500
2	02T-01B	81.00	2,025	5	1,920	95%	1,710	-	1,540
4	02T-02B	162.00	4,050	30	11,520	284%	1,960	-	1,540
6	02T-03B	243.00	6,075	40	15,360	253%	2,055	1,500	1,500
8	02T-04B	324.00	8,100	60	23,040	284%	2,150	1,500	1,500
3	03T-01B	121.50	3,038	5	1,920	63%	1,710	-	1,540
6	03T-02B	243.00	6,075	46	17,664	291%	1,960	-	1,540
9	03T-03B	364.50	9,113	60	23,040	253%	2,055	1,500	1,500
12	03T-04B	486.00	12,150	90	34,560	284%	2,150	1,500	1,500
4	04T-01B	162.00	4,050	5	1,920	47%	1,710	-	1,540
8	04T-02B	324.00	8,100	62	23,808	294%	1,960	-	1,540
12	04T-03B	486.00	12,150	82	31,488	259%	2,055	1,500	1,500
16	04T-04B	648.00	16,200	124	47,616	294%	2,150	1,500	1,500

The research conducted in this chapter has been incorporated in the design of a hybrid urban vertical farm. Now, at its conclusion, references are made to the chapters in which the features identified as important in this chapter have been incorporated into the design.

- The optimization to the layout of module configurations is used in the next optimization, which looks at how to reuse as many midfield columns in a configuration as possible (p5 optimize c3 columns).

in this chapter

Module configurations are built by linking modules, and all modules use one or more midfield columns in their steel structure. Growing systems also use midfield columns in their structure; and many growing systems fit in even the smaller module configurations. But there is only a limited amount of midfield columns reclaimable from MightyVine phase 3: only 704. To get to the highest reuse percentage for all components that midfield components are the benchmark, as these are reused the most frequent and run out before all other components will. That is why, in this chapter, the balance between module configuration size and the growing systems in them is studied to find out which design (modules plus growing systems) in total comes closest to reusing all 704 midfield columns. That design will be the optimal hybrid urban vertical farm that can be built with reused greenhouse components from MightyVine phase 3.

midfield column use

To determine how efficient module configurations reuse the 704 midfield of MightyVine phase 3, two calculations are done: first, a calculation of how many midfield columns are reused in the construction of 84 different module configurations. Second it is studied how many midfield columns are needed to build the amount of single and coupled systems that fit in each module configuration. In p5 optimize c2 fsi it was found that in an 1T2B configuration there fit five single systems and five coupled systems , and in an 2T2B configuration eleven single systems and ten coupled systems fit. In the previous chapter this was done for sixteen module configurations, all graphically supported as well. In this chapter, it is done for 84 module configurations. However, it is only done for module configurations with an even number of bays up to a lenght of 14 trellises. This results from the previous chapters' conclusion that it is best to build module configurations with an even number of bays and as many trellises as possible. In *table 6* the number of columns required for the construction of the modules **and** growing systems is summed, to get an overview which module configuration (including growing systems) comes closest to reusing 704 midfield columns, and thus is the optimal hybrid urban vertical farm module configuration.

script

A Grasshopper/OpenNest nesting script is used to determine how many uncut midfield colulmns are needed to get all the parts for single and coupled systems from the reclaimed columns as efficiently as possible. That way as little material as possible is wasted. Presumably mistakes will be made during construction/cutting, so it is recommended to be slightly below 100% reuse of columns at midfield to have some reserve.

results

Table 6 shows the number of single systems and coupled systems that fit into each configuration in [Single] and [Coupled]. Next is the number of midfield columns that are required to build that amount of growing systems (when, using the script, utilized as efficient as possible) in [System]. The maximum number of trellises is capped at 14, because this is the number of trellises in the endwalls of MightyVine phase 3. Since the case study has 51 sidewalls in the east sidewall only, one cannot built a closed module configuration of 51 bays deep, beause that would require twice as much sidewalls as there are available. Hence, in theorie there are 51/2 = 25.5 = 25 bays availble; but it has already been calculated that an even number of bays leads to a higher floor space index, so the recommendation is to build module configurations with a maximum of 24 bays). Because the calculations in *table 6* indicate that there are not enough columns to build and fill 24 bays with growing systems, the list is capped at 14T14B.

In green, the highest reuse percentage of all module configurations that remain below 704 midfield columns are highlighted, and the most efficient one, 8T4B, is highlighted orange.

table 6: midfield column reuse percentages of module configurations (own, 2023)

	Systems		Columns					Systems		Columns			
Conf.	Single	Coupled	Systems	Modules	Total	Reuse	Conf.	Single	Coupled	Systems	Modules	Total	Reuse
1T2B	5	5	39	0	39	5%	1T8B	10	22	132	0	132	19%
2T2B	11	10	80	1	81	12%	2T8B	43	39	313	7	320	45%
3T2B	16	15	119	2	121	17%	3T2B	63	59	467	14	481	68%
4T2B	22	20	160	3	163	23%	4T8B	87	81	642	21	663	94%
5T2B	27	25	199	4	203	29%	5T8B	107	101	796	28	824	117%
6T2B	33	30	240	5	245	35%	6T8B	131	123	972	35	1,007	143%
7T2B	38	35	279	6	285	40%	7T8B	151	143	1,126	42	1,168	166%
8T2B	44	40	320	7	327	47%	8T8B	175	165	1,302	49	1,351	192%
9T2B	49	45	359	8	367	52%	9T8B	195	185	1,456	56	1,512	215%
10T2B	55	50	401	9	410	58%	10T8B	219	207	1,631	63	1,694	241%
11T2B	60	55	439	10	449	64%	11T8B	239	227	1,785	70	1,855	264%
12T2B	66	60	481	11	492	70%	12T8B	263	249	1,961	77	2,038	289%
13T2B	71	65	519	12	531	75%	13T8B	283	269	2,115	84	2,199	312%
14T2B	77	70	561	13	574	81%	14T8B	307	291	2,290	91	2,381	338%
1T4B	0	14	64	0	64	9%	1T10B	5	31	158	0	158	22%
2T4B	22	19	156	3	159	23%	2T10B	54	48	388	9	397	56%
3T4B	32	29	233	6	239	34%	3T10B	79	73	581	18	599	85%
4T4B	44	40	320	9	329	47%	4T10B	109	101	803	27	830	118%
5T4B	54	50	397	12	409	58%	5T10B	134	126	995	36	1,031	146%
6T4B	66	61	485	15	500	71%	6T10B	164	154	1,217	45	1,262	179%
7T4B	76	71	562	18	580	82%	7T10B	189	179	1,409	54	1,463	208%
8T4B	88	82	650	21	671	95%	8T10B	219	207	1,631	63	1,694	241%
9T4B	98	92	727	24	751	107%	9T10B	244	232	1,824	72	1,896	269%
10T4B	110	103	815	27	842	120%	10T10B	274	260	2,045	81	2,126	302%
11T4B	120	113	892	30	922	131%	11T10B	299	285	2,238	90	2,328	331%
12T4B	132	124	980	33	1,013	144%	12T10B	329	313	2,460	99	2,559	363%
13T4B	142	134	1,057	36	1,093	155%	13T10B	354	338	2,652	108	2,760	392%
14T2B	154	145	1,144	39	1,183	168%	14T2B	384	366	2,874	117	2,991	425%
1T6B	5	17	94	0	94	13%	1T12B	10	34	187	0	187	27%
2T6B	32	29	233	5	238	34%	2T12B	64	58	465	11	476	68%
3T6B	47	44	348	10	358	51%	3T12B	94	88	696	22	718	102%
4T6B	65	61	482	15	497	71%	4T12B	130	122	964	33	997	142%
5T6B	80	76	598	20	618	88%	5T12B	160	152	1,195	44	1,239	176%
6T6B	98	93	732	25	757	107%	6T12B	196	186	1,463	55	1,518	216%
7T6B	113	108	847	30	877	125%	7T12B	226	216	1,694	66	1,760	250%
8T6B	131	125	981	35	1,016	144%	8T12B	262	250	1,962	77	2,039	290%
9T6B	146	140	1,097	40	1,137	161%	9T12B	292	280	2,193	88	2,281	324%
10T6B	164	157	1,231	45	1,276	181%	10T12B	328	314	2,461	99	2,560	364%
11T6B	179	172	1,346	50	1,396	198%	11T12B	358	344	2,692	110	2,802	398%
12T6B	197	189	1,480	55	1,535	218%	12T12B	394	378	2,960	121	3,081	438%
13T6B	212	204	1,596	60	1,656	235%	13T12B	424	408	3,191	132	3,323	472%
14T6B	230	221	1,730	65	1,795	255%	14T12B	460	442	3,459	143	3,602	512%

From *table 6* it can be concluded that **the optimal module configuration is an 8T4B**, that is eight trellises long and four bays deep. The construction of the modules requires 21 midfield columns, and the construction of 88 single systems and 82 coupled systems requires 650 midfield columns that can be cut to create the smaller parts (verticals, arms, and feet). A total of 671 columns are required for an 8T4B module configuration, leading to a reuse rate of midfield columns of 95%. Other configurations have either *lower* reuse rates, resulting in *less efficient* use of reclaimable components, or *higher* reuse rates, which means more components are needed than can be recovered, so *new* components must be produced.

case study versus huvf

Now that the optimal module configuration for hybrid urban vertical farming is known, the modules needed to build both the original greenhouse, case study MightyVine phase 3, **and** the 8T4B module configuration can be compared. This is done visually (*figure 66*), and is the starting point of the carbon footprint comparison in p6 carbon c3 compare. That chapter will also tabulate the difference in modules required.

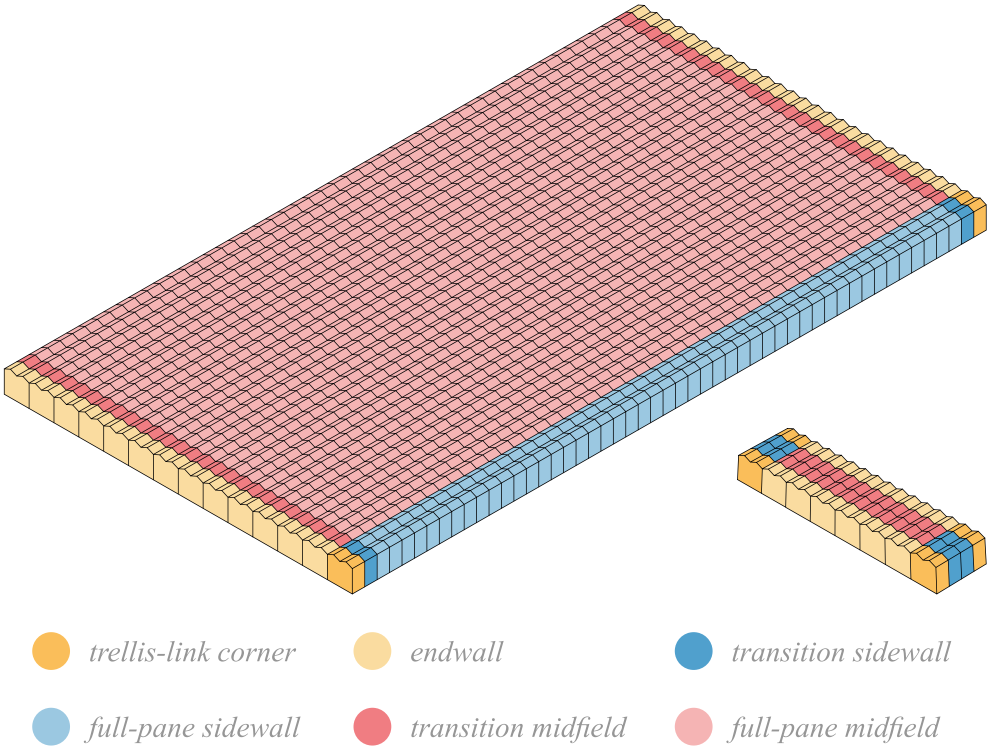


figure 66: required modules for MightyVine phase 3 (l) and an 8T4B module configuration (r) (own, 2023)

The research conducted in this chapter has been incorporated in the design of a hybrid urban vertical farm. Now, at its conclusion, references are made to the chapters in which the features identified as important in this chapter have been incorporated into the design.

- The conclusion that an 8T4B module configuration is optimal for a hybrid urban vertical farm module configuration, is the premise of the carbon footprint calculation of a huvf (p6 carbon c1 modules).

The research in each part is conducted to answer one or more sub-research questions, which will ultimately help answer the main research question. These sub research questions are answered by means of a certain product, identified in p1 intro c3 research. The results are discussed here.

In p5 optimize two sub research questions have been answered, the fifth and sixth one. The questions and the approach to finding an answer to it were:

5. Regarding the aspect "sustainable, and economically feasible": "*How can as much daylight be utilized to minimize energy costs for artificial lighting?*". It is answered in p5 optimize by means of an optimization of the orientation of systems to receive maximum daylight **and** an optimization of the spacing between systems to receive maximum daylight.

This question is answered in c1 light. To provide a concise answer to this question, a summary of the conclusion of the light optimization is given below:

The light optimizations show that it is best to rotate growing systems *in sync* without spacing. Annually, 34% of the photosynthetic photon flux density (PPFD) requirement of crops can be met with daylight, compared to 45% (at 730 mm spacing; a *half* configuration) and 53% (at 1,460 mm spacing; a *full* configuration). However, a *zero* configuration, a configuration with no spacing, can utilize an available footprint 100%, compared to 67% and 56% for a half and full configuration, respectively. Thus, 34% can be saved on artificial lighting on annually by utilizing as much daylight as possible and maximizing the footprint utilization. Nine lights are needed to supplement PPFD in December; in spring, summer, and fall the lights can be attenuated to consume less energy because crops then receive more PPFD through more intense sunlight.

6. Regarding the aspect "become high yielding": *"How can a growing system use an available footprint efficiently?"*. This is answered in p5 optimize by means of an optimization of growing system placement in modules to obtain the highest floor space index (FSI) **and** an optimization of a module configuration to get the highest possible reuse percentage of a case study greenhouse's components

This question is answered in c2 fsi. To provide a concise answer to this question, a summary of the conclusion of the FSI optimization is given below:

The FSI optimization resulted in four findings, first, it is not recommended to build a module configuration of multiple trellises long and only one bay deep, because due to the midfield bracing between the modules only the first module will be accessible. Second, it is recommended to connect as many trellises together as the construction site/urban infrastructure allows, to minimize the relative amount of sidewall space. Third, it is best to connect an even number of bays together to get the relative amount of walkspace as close to 25% as possible, compared to 50% (one bay) or 67% (an odd number of bays) and use most of the depth of the module configurations to set up growing systems. Finally, fourth, it is beneficial to build growing systems as high as possible because every 800 mm extra height equals two extra containers, which increases the floor area index (fsi) greater and faster than any other design optimization could achieve.

part six

carbon

p6

carbon

in this part

In p6 carbon *everything comes together. This whole research is about reuse of components. And now it is time to investigate how sustainable hybrid urban vertical farming really is compared to the conventional farming practice of the case study performs: greenhouse agriculture. The question answered in this part is: what is the carbon footprint of the new materials in the construction of the modules and the construction of the growing systems? Is it lower for an 8T4B module configuration than for MightyVine phase 3? Or is it the other way around, and does this thesis conclude that hybrid urban vertical farming does have a three times higher footprint utilization (see* c3 compare*) but is not (yet) more sustainable than existing farming practices?*

In p1 module *the carbon footprint of the modules is calculated, in* p2 system *the same is done for the growing systems. A distinction is always made so components that are reused and components that are new, obviously, because that is the premise of this thesis. Finally,* p3 compare *looks at which components (modules, bracing, growing systems) are in the optimal 8T4B hybrid urban vertical farm, and which are in MightyVine phase 3. Then follows the most important comparison of this thesis: their carbon footprint is divided by the number of crops that can be cultivated in the greenhouse per growth cycle, this determines the carbon footprint per crop... And that, that is the deciding factor in designating the more sustainable farming practice of the two.*

c1 modules

c2 system

c3 compare

c1

modules

in this chapter

MightyVine phase 3 is essentially build of modules, just like a hybrid urban vertical farm. However, there are two differences between the two. First, the case study greenhouse is bigger, of 14 trellises (126 meters) long and 51 bays (229.5 meters) deep it has a footprint of 28,917 m^2. An 8T4B module configuration of 8 trellises (72 meters) long and 4 bays (18 meters) deep has a footprint of 1,296 m^2. Second, the greenhouse was build using only new components, whilst a hybrid urban vertical farm reuses many components. Both result in different carbon footprints. In this chapter, it is calculated what the carbon footprint of the different modules is, both for a new greenhouse, and for a component reusing hybrid urban vetical farm.

approach

To calculate the carbon footprint of the modules that were designed in p3 module c3 design, each is modeled in detail in 3D. *Per* module *per* material *per* component, the volume of components is calculated. The model gives the volume with an precision of 10^{-12} m^3, so the accuracy of data in appendix 7 (which presents a breakdown of the carbon footprint calculation of each module), goes well beyond five decimal places. By multiplying the volume of each component by the density of the material it is made of, its mass is calculated. Then, by multiplying its mass by the production factor that is assigned to the material that it is made of, the carbon footprint of each component is calculated. Production factors give the carbon equivalent emissions ($CO_{2\text{-eq}}$ emissions) in kg that are released in the production of 1 kg of a material. By summing the $CO_{2\text{-eq}}$ emissions of all components in each of the modules, the carbon footprint of each module is calculated.

Because certain components are shared by modules, such as a trellis on the module boundary of a corner and a sidewall module, for example, they are divided over modules. This way, the components thar are shared between modules have an equal share in the carbon footprint determination of both modules. Besides, since not every endwall, sidewall, and midfield module needs bracing, the carbon footprint of bracing in the gables and in the deck is calculated separately. These are **later added** to the total carbon footprint of both the greenhouse and the 8T4B module configuration. First gutter row bracing is present in every corner and sidewall module, so these are **already included** in the carbon footprint of the modules.

The construction of the gables and deck consists lots of aluminum profiles, sealing rubbers, and PVC strips. If these are all listed in the carbon footprint analysis, the list becomes very long. In the carbon footprint analysis of the gable, it was therefore chosen to group those components per endwall and sidewall into vertical and horizontal components per material (aluminum, rubber, and PVC). To do this, the total length of components in each group is multiplied by the cross-sectional area of the components. In appendix 6a, all components in the gable are imaged in three annotated details, and cross-sectional areas are tabulated.

A similar approach was taken for the deck construction, here the various components are grouped by material under the three main components gutter, ridge, and window frame. Again, the cross-sectional areas were multiplied by the length of the components to arrive at the total volume. In appendix 6b, all components in the deck are depicted in three annotated details, and cross-sectional areas are tabulated.

production factors

Table 7 summarizes the used densities [Density] and production factors [Production factor] of the materials that are used to construct modules. The sources are listed in [Source], and are included in the bibliography.

Important: production factors can vary based on what is and what is not included in their calculation. The production factors in *table 7* reflect only the $CO_{2\text{-eq}}$ emissions released from the productions, they do not take into account transportation, construction and any demolition and rebuilding.

table 7: densities and production factors of materials used in modules (own, 2023)

Material [-]	Density [kg/m^3]	Production factor [kg$CO_{2\text{-eq}}$/kg]	Source [-]
Aluminium	2,700	16.64	(International Aluminium, 2021)
Concrete	2,400	1.02	(Mahasenan et al., 2003)
Galvanized steel	7,850	1.80	(Galvanizeit, n.d.)
Glass	2,500	0.68	(Ecofys & Fraunhofer-ISI, 2009)
PVC	1,330	2.18	(Primo, 2020)
Rubber	1,500	3.45	(Bergsma et al, 2021)
Stainless steel	7,850	1.91	(World Steel Association, 2021)

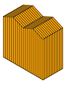
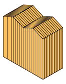
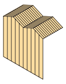
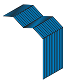
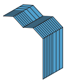
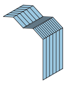
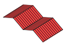
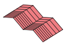
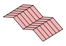
Steel has a lower production factor compared to other materials due to its simpler production process and the ability to use recycled steel. Aluminum has the highest production factor because it requires a lot more energy and the extraction of bauxite is energy-intensive. Concrete has a relatively low production factor since it mainly consists of locally available materials like sand, gravel, and water. Its manufacturing process is straightforward, and the material has a long lifespan. Glass also has a relatively low production factor because it uses locally available materials and has a long lifespan. Additionally, its recycling process has a smaller environmental impact compared to aluminum and steel. Rubber has a higher production factor than steel and concrete due to the energy required for its production, including the extraction, transportation, and processing of natural resources. PVC, among all the materials used in modules, has the highest production factor. This is because it has high energy requirements and relies on fossil fuels during its production process. Furthermore, the manufacturing of PVC releases hazardous by-products that harm the environment.

results: modules

In appendix 7a, appendix 7b, and appendix 7c, contain the carbon footprint breakdown for the modules. The tables are structured by first naming the main group to which components belong [Group]. Then the material from which a component is made is named in [Material] and the component itself is named in [Component]. For each component, [R/N] indicates whether the component is new or is a reused greenhouse component. Using the 3D model, the volume of components is calculated for each module per material. Using *table 7*, the volume can be converted to a mass in kilograms in [Weight]. Then, again using *table 7*, that mass is multiplied by the production factor of each component material, to arrive at a carbon footprint of the component. At the bottom of the tables, where '*Total*' appears in [Group], the total weight of each module is listed under [Weight], as well as *new* (absolute mass), *new %* (percentage of total mass), *reuse*, and *reuse %*. The same is done under [Footprint], now for the carbon footprint. This data is also divided into *new*, *new %*, *reuse*, and *reuse %*.

In *table 8* a summary is given, providing the data that is summarized in the tables of appendix 7a-7c. For each module the total carbon footprint is given, and the proportion of new components (absolute and percentage) and reused components (absolute and percentage) have in it. **Note:** the total carbon footprint of the modules is essentially *equal* to the carbon footprint of the once newly built modules in MightyVine phase 3, because in that construction no components were reused at all, but all were new.

table 8: summary of the carbon footprint of modules and bracing (own, 2023)

module	total*	new*	new %	reuse*	reuse %
 bay-link corner	14,614	7,272	50%	7,343	50%
 trellis-link corner	14,489	7,269	50%	7,220	50%
 endwall	9,623	5,273	55%	4,351	45%
 half-pane sidewall	6,766	2,814	42%	3,951	58%
 transition sidewall	6,555	2,811	43%	3,744	57%
 full-pane sidewall	6,345	2,808	44%	3,538	56%
 half-pane midfield	2,742	650	24%	2,092	76%
 transition midfield	2,722	650	24%	2,073	76%
 full-pane midfield	2,704	650	24%	2,054	76%
endwall bracing	18.24	0	0%	18.24	100%
sidewall bracing	92.23	0	0%	92.23	100%
midfield bracing	148.47	0	0%	148.47	100%
deck bracing	15.42	0	0%	15.42	100%

** all absolute carbon footprints are given in* $kgCO_{2\text{-}eq}$

results: bracing

A similar calculation is done for bracing that occurs in endwalls, sidewalls, the roof, and in midfield modules. The carbon footprint breakdown of them is included in appendix 8. In *table 8* these are summarized too, at the end of the table. As all bracings can be reused, the proportion of reuse is 100%.

conclusion

By calculating the carbon footprint using the volumes, masses, and production factors of all components, an overview of the carbon footprint of the nine modules and the four types of bracing has now been composed in *table 8*. These can be multiplied in p6 carbon c3 compare by the number of modules and bracings used to build MightyVine phase 3 and an 8T4B module configuration, to determine the total carbon footprint of both assembled constructions.

The research conducted in this chapter has been incorporated in the design of a hybrid urban vertical farm. Now, at its conclusion, references are made to the chapters in which the features identified as important in this chapter have been incorporated into the design.

- The calculated carbon footprint of the modules is used to compare the total carbon footprint of MightyVine phase 3 and an 8T4B module configuration (p6 carbon c1 modules).

in this chapter

Growing systems are placed in module configurations, and their components increase the overall carbon footprint of a hybrid urban vertical farm. To calculate the carbon footprint of both the single and coupled growing systems, this chapter uses a similar approach as the previous chapter. Some major improvements in material use are made during the research, so both the old and improved carbon footprints are discussed.

approach

To calculate the carbon footprint of a single system and a coupled system, again a 3D model was used from which the volume per system type per material per component was determined with a precision of 10^{-12} m^3. From there the weight and carbon footprint were calculated. Densities and production factors from *table 9* are used, the sources are listed in [Source], and are included in the bibliography.

table 9: densities and production factors of materials used in growing systems (own, 2023)

Material [-]	Density [kg/m^3]	Production factor [kgCO$_{2\text{-eq}}$/kg]	Source [-]
Aluminium	2,700	16.64	(International Aluminium, 2021)
Concrete	2,400	1.02	(Mahasenan et al., 2003)
Galvanized steel	7,850	1.80	(Galvanizeit, n.d.)
Mosswool	1,250	2.20	(International Peatland Society, 2021)
Polycarbonate	1,200	1.10	(PBL Netherlands Environmental Assessment Agency, 2021)
Rubber	1,500	3.45	(Bergsma et al, 2021)
Stainless steel	7,850	1.91	(World Steel Association, 2021)

improvements

In the original growing system design, two things were different: first, the container fronts and bottoms were not made of 2.5 mm hardened polycarbonate with a low production factor of 1.10 kgCO$_{2\text{-eq}}$, but of 5 mm aluminum with a production factor of 16.64 kgCO$_{2\text{-eq}}$. The NFT system and irrigation slit were also made of aluminium instead of polycarbonate. Second, the previous version assumed a 15 mm concrete floor over the entire footprint of the modules on which rails were placed. In the improvement that floor is replaced by 190 mm concrete beams that run only under the feet of growing systems, of which 150 mm are under the rails, and 40mm around the rails (for encapsulation). The change from a concrete floor to concrete beams to support growing systems reduced the carbon footprint of the modules because the floor was allocated to module construction. *Table 10* lists the old and new carbon footprints of the modules, including the (**great**) reductions as a percentage in [Reduction].

table 10: carbon footprint reduction in modules by removing a concrete floor (own, 2023)

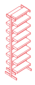
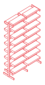
Module [-]	Original design footprint [kgCO$_{2\text{-eq}}$]	Improved design footprint [kgCO$_{2\text{-eq}}$]	Reduction [-]
Bay-link corner	29,030	14,614	50%
Trellis-link corner	28,905	14,489	50%
Endwall	24,135	9,623	60%
Half-pane sidewall	21,576	6,766	69%
Transition sidewall	21,365	6,555	69%
Full-pane sidewall	21,155	6,345	70%
Half-pane midfield	17,650	2,742	84%
Transition midfield	17,630	2,722	85%
Full-pane midfield	17,612	2,704	85%

Lowering the carbon footprint by removing a concrete floor is important, because the case study MightyVine phase 3 does not have a concrete floor (its growing system is suspended from the steel structure). If a hybrid urban vertical farm would have a concrete floor then it is already immediately much more unsustainable than any other farming practice that does not.

results

The reconsideration of the material for container fronts and bottoms greatly reduced the carbon footprint of growing systems, but, now concrete beams are also allocated to growing system constructions. The carbon footprint calculations of the original and improved design of growings systems are, in that order, included in appendix 9a and appendix 9b. Again, at the bottom of the tables, the total carbon footprint is added up, as well as the proportion of new and reused parts, both in absolute and percentage terms. **Note**: it is not difficult to determine the carbon footprint of a drive motor and lights without product knowledge, so these have been left blank. They are also not included in the carbon footprint of the case study. A summary of the carbon footprint of the old and the improved growing systems is presented in *table 11*. It can be concluded that the change from aluminium to polycarbonate containers and NFT systems is beneficial. **The improved single system has a carbon footprint of 20.21% compared to its original design. For the coupled system that is 17.72%. Due to the lower overall carbon footprint, the proportion of reuse has increased by 14 percentage points (single system) and 23% (coupled system).**

table 11: summary of the carbon footprint of original and improved growing systems (own, 2023)

growing system	total*	new*	new %	reuse*	reuse %
 single original	12,428	11,970	96%	458	4%
 single improved	2,512	2,052	82%	460	18%
 coupled original	24,364	23,670	97%	694	3%
 coupled improved	4,318	3,620	84%	698	26%

** all absolute carbon footprints are given in kgCO$_{2\text{-eq}}$*

The research conducted in this chapter has been incorporated in the design of a hybrid urban vertical farm. Now, at its conclusion, references are made to the chapters in which the features identified as important in this chapter have been incorporated into the design.

- The calculated carbon footprint of the growing systems is used to compare the total carbon footprint of MightyVine phase 3 and an 8T4B module configuration (p6 carbon c1 modules).

in this chapter

Having calculated the carbon footprint of modules and growing systems, it can now be examined whether a hybrid urban vertical farm comes close to the sustainability of one of the trational farming practices: greenhouse agriculture. To this end, this chapter first calculates how many crops can be grown in both the case study greenhouse and an 8T4B module configuration. Then the carbon footprint of the modules plus growing systems is divided by this. Which farming practice has the lowest carbon footprint per crop?

crops

The case study, MightyVine phase 3, has a footprint of 14 trellises of 9,000 mm long by 51 bays of 4,500 mm long. This is 29,917 m^2, or 2.9 hectares. However, not the entire footprint is used for crop cultivation, as there is one concrete center aisle where no crops grow; that aisle is used to access the paths in which crops grow and transport tomatoes to the storage. This leaves a growing surface of 14 trellises x 9 meters x 50 bay x 4.5 meters = 28,350 m^2. As was assumed in p4 system c2 typologies, a one-layer growing system can use 95% of its footprint effectively as growing surface. So, 95% x 28,350 m^2 = 26,932.5 m^2 of MightyVine phase 3 can be used for lettuce cultivation using a one-layer growing system. Knowing that a lettuce crop needs 0.04 m^2 to grow, the greenhouse can grow 26,932.5 / 0.04 = 673,313 crops in one growth cycle.

In an 8T4B module configuration there is space for 88 single systems and 82 coupled systems, respecting sidewall space, walkspace, and workspace, as was calculated in p5 optimize c3 columns. Thus, there are 88 + 2 x 82 = 252 sets of 16 rotating containers present in that optimal configuration. As one container holds four trays in which 24 crops grow, a total of 252 x 16 x 4 x 6 = 96,768 crops can be grown in one growth cycle in an 8T4B module configuration. These grow in a module configuration of 8 trellises x 9 meters by 4 bays x 4.5 meters, or on a footprint of 1,296 m^2.

Now the first conclusion can be made: in an 8T4B module configuration 96,768 crops grown on 1,296 m^2. That is 96,768 / 673,313 = 14.4% of the crops that the case study greenhouse can grow in one growth cycle on only 1,296 / 26,932.5 = 4.8% of the footprint. The hybrid urban vertical farm grows 96,768 crops / 1,296 m^2 = 74.7 crops/m^2. The greenhouse grows 673,313 crops / 29,917 m^2 = 22.5 crops/m^2. **Thus, the hybrid urban vertical farm is 74.7 / 22.5 = 3.3 times more efficient in terms of footprint utilization.**

modules

To determine the carbon footprint per crop, the carbon footprint of the structure must be known. MightyVine Phase 3 was built by linking the following modules together, visualized in *figure 67*:

- 002 corner modules;
- 004 endwall modules with shoring;
- 020 endwall modules without shoring;
- 002 sidewall modules with shoring and with bracing;
- 002 sidewall modules with shoring and without bracing;
- 047 sidewall modules without shoring;
- 026 midfield modules with shoring and with bracing;
- 026 midfield modules with shoring and without bracing;
- 585 midfield modules without shoring and without bracing.

Important: because concrete has a major impact on the carbon footprint of a structure because it occurs in such larger volumes, the concrete center aisle of MightyVine phase 3 is also included in determining the carbon footprint of the greenhouse. Like the bracing, it is added to the carbon footprint of the modules.

An 8T4B module configuration is built by linking the following modules together, visualized in *figure 67*:

- 4 corner modules;
- 2 endwall modules with shoring;
- 10 endwall modules without shoring;
- 2 sidewall modules with shoring and with bracing;
- 2 sidewall modules without shoring and without bracing;
- 6 midfield modules with shoring and with bracing;
- 6 midfield modules without shoring and without bracing;

Table 12 lists the modules and bracing in the case study greenhouse and in an 8T4B module configuration in [Element] and their number in [Number]. For the greenhouse, the total carbon footprint of modules is given in [Footprint], for the hybrid urban vertical farm only the carbon footprint of new components is given. **The total carbon footprint per type of module is shown in [Total], and summed at the bottom.**

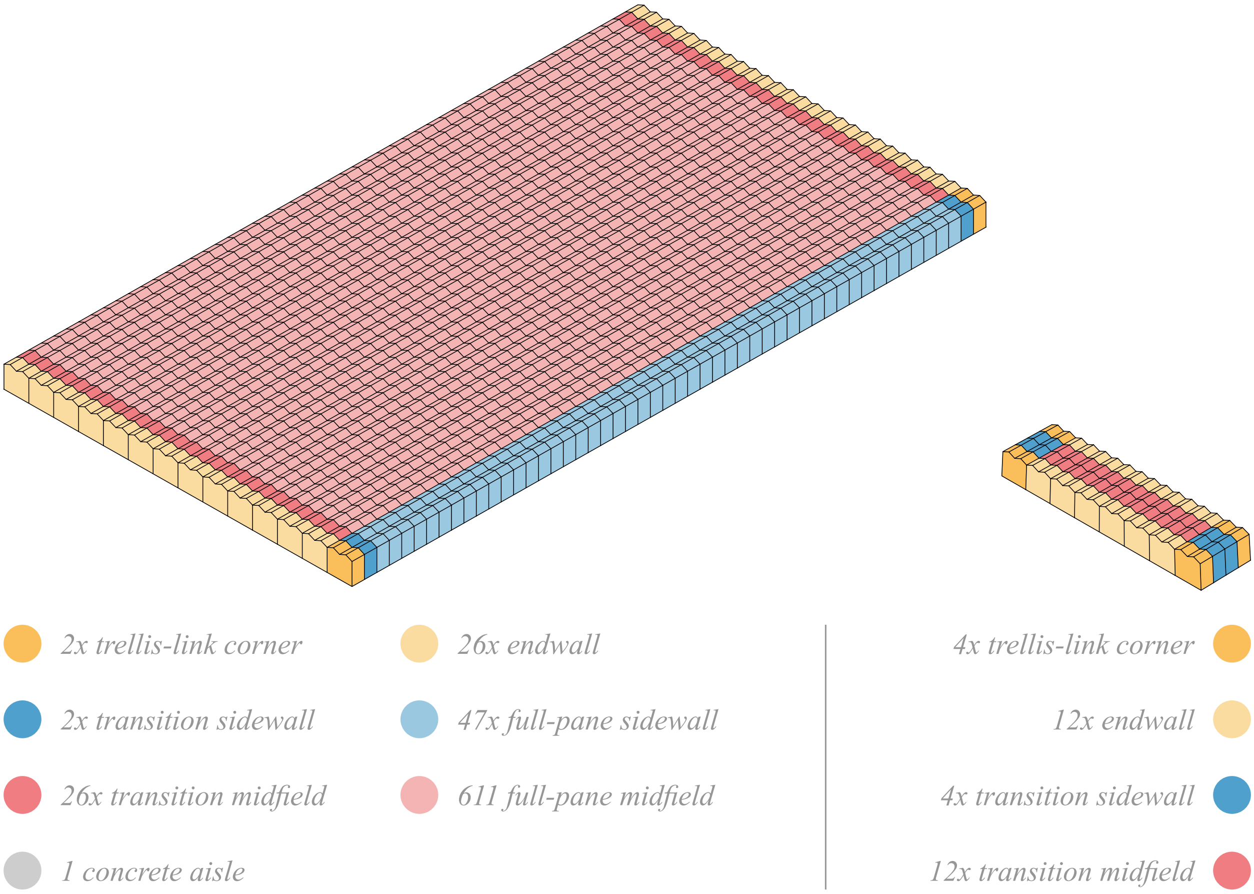


figure 67: required modules for MightyVine phase 3 (l) and an 8T4B module configuration (r) (own, 2023)

The carbon footprint of the concrete center aisle in the greenhouse is 14 trellises long, 1 bay wide, and 150 mm thick. Thus, its volume is 14 x 9 x 1 x 4.5 x 0.15 = 85.05 m^3. Concrete has a density of 2,400 kg/m^3 and a production factor of 1.02. Therefore, its carbon footprint is 85.05 x 2,400 x 1.02 = 208,202 $kgCO_{2\text{-eq}}$.

table 12: carbon footprint per crop resutling from constructing modules (own, 2023)

MightyVine phase 3 case study greenhouse

Element [-]	Number [#]	Footprint (total) [$kgCO_{2\text{-eq}}$]	Total [$kgCO_{2\text{-eq}}$]
Bay-link corner	0	14,614	-
Trellis-link corner	2	14,489	28,978
Endwall	26	9,623	250,199
Half-pane sidewall	0	6,766	-
Transition sidewall	2	6,555	13,110
Full-pane sidewall	47	6,345	298,224
Half-pane midfield	0	2,742	-
Transition midfield	26	2,722	70,785
Full-pane midfield	611	2,704	1,651,986
Endwall bracing	4	18	73
Sidewall bracing	4	93	371
Midfield bracing	52	148	7,720
Deck bracing	54	15	823
Concrete center aisle	1	208,202	208202
Total			2,530,472

Hybrid urban vertical farm 8T4B module configuration

Element [-]	Number [#]	Footpring (new) [$kgCO_{2\text{-eq}}$]	Total [$kgCO_{2\text{-eq}}$]
Bay-link corner	0	7,272	-
Trellis-link corner	4	7,269	29,078
Endwall	12	5,273	63,275
Half-pane sidewall	0	2,814	-
Transition sidewall	4	2,811	11,244
Full-pane sidewall	0	2,808	-
Half-pane midfield	0	650	-
Transition midfield	12	650	7,799
Full-pane midfield	0	650	-
Endwall bracing	2	18	36
Sidewall bracing	2	93	185
Midfield bracing	7	148	1,039
Deck bracing	14	15	213
Total			112,871

Table 12 shows that the carbon footprint of the case study, resulting from constructing modules, is 2,530,472 $kgCO_{2\text{-eq}}$/ 112,871 $kgCO_{2\text{-eq}}$ = 22.4 times higher than the carbon footprint of the 8T4B module configuration. This is caused, first, by the smaller footprint of the hybrid urban vertical farm, and second, by reuse of components in hybrid urban vertical farm modules (50-76% of the carbon footprint of modules, see p6 carbon c1 modules). The carbon footprint per crop that results from constructing modules is:

- For MightyVine phase 3: 2,530,472 $kgCO_{2\text{-eq}}$ / 673,313 crops = 3.76 $kgCO_{2\text{-eq}}$/crop;
- For an 8T4B module configuration: 112,871 $kgCO_{2\text{-eq}}$ / 96,768 crops = 1.17 $kgCO_{2\text{-eq}}$/crop.

This means, if the growing systems do not increase the total carbon footprint per crop with more than 2.59 $kgCO_{2\text{-eq}}$/crop, that hybrid urban vertical farming could be more sustainable than greenhouse agriculture.

systems

As mentioned before, in an 8T4B module configuration there is space for 88 single systems and 82 coupled systems. *Table 13* lists the total carbon footprint of that number of growing systems. Under [Growing system] the type of growing system is named, and under [Footprint] the carbon footprint caused by use of new components is given. The totals are listed in [Total].

table 13: carbon footprint per crop resulting from constructing growing systems (own, 2023)

Growing system [-]	Number [#]	Footpring (new) [$kgCO_{2\text{-eq}}$]	Total [$kgCO_{2\text{-eq}}$]
Single system	88	2,052	180,587
Coupled system	82	3,620	296,862
Total			477,449

Table 13 shows that the carbon footprint resulting from constructing growing systems is 477,449 $kgCO_{2-eq}$. The carbon footprint per crop resulting from constructing growing systems is:

- For an 8T4B module configuration: 477,449 $kgCO_{2-eq}$ / 96,768 crops = 4.93 $kgCO_{2-eq}$/crop.

For an 8T4B module configuration, this is 4.23 times more than the carbon footprint per crop resulting from constructing the modules. (1.17 $kgCO_{2-eq}$/crop for the growing systems/ 4.93 $kgCO_{2-eq}$/crop for the modules = 4.23). **Therefore,** the influence on the carbon footprint of a hybrid urban vertical farm is mainly determined by the carbon footprint of the growing systems, and slightly by the modules. Unfortunately 1.17 $kgCO_{2-eq}$/crop for the growing systems is more than the 2.59 $kgCO_{2-eq}$/crop margin that was left in order for hybrid urban vertical farming to be at least equally sustainable as greenhouse agriculture. This indicates that a hybrid urban vertical farm is thus, in terms of the carbon footprint resulting from constructing modules and growing systems, less sustainable than greenhouse agriculture. However, in this calculation, the growing systems in MightyVine phase 3 are not included, this will be reflected upon later.

total carbon footprint

In *table 14* the composition of the total carbon footprint of the case study greenhouse Mightyvine phae 3 and an optimal 8T4B module configuration is presented. Per type of module, bracing, concrete center aisle (only in the greenhouse) and growing system (only in the hybrid urban vertical farm) the number of times that element occurs is given, as well as the total carbon footprint of that many of that element. For the case study the total carbon footprint of those elements is used as they are calculated in p6 carbon c1 module, because all its components were new during construction. For the hybrid urban vertical farm only the proportion of new components is used as they are calculated in p6 carbon c1 module en p6 carbon c2 system, because some of its components will be new and many components will be reused during construction.

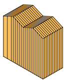
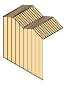
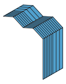
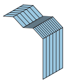
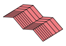
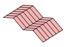
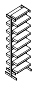
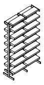
When adding the [Footprint (total)] of all elements in MightyVine phase 3 in *table 14*, the total carbon footprint of the case study greenhouse is 2,530,472 $kgCO_{2-eq}$. As it can grow 673,313 crops in one growth cycle, the carbon footprint per crop is 2,530,472 $kgCO_{2-eq}$ / 673,313 crops = **3.75 $kgCO_{2-eq}$/crop**.

When adding the [Footprint (new)] of all elements in the hybrid urban vertical farm in *table 14* , the total carbon footprint of the case study greenhouse is 590,320 $kgCO_{2-eq}$. As it can grow 96,768 crops in one growth cycle, the carbon footprint per crop is 590,320 $kgCO_{2-eq}$ / 96,768 crops = **6.10 $kgCO_{2-eq}$/crop**.

It can be concluded, when assessing greenhouse agriculture and hybrid urban vertical farming **only** on the carbon footprint resulting from the production of materials that are used for constructing modules, bracing, a concrete center aisle, and growing systems, that **hybrid urban vertical farming is less sustainable than greenhouse agriculture by a factor 6.10 $kgCO_{2-eq}$/crop ÷ 3.75 $kgCO_{2-eq}$/crop = 1.63, or 163%**.

The previous version of the design had concrete floors and aluminum containers and NFT systems, Then, the carbon footprint per crop was 1.7 $kgCO_{2-eq}$/crop (modules) + 24.25 $kgCO_{2-eq}$/crop (growing systems) = 25.95 $kgCO_{2-eq}$/crop. After changes, that is 1.17 $kgCO_{2-eq}$/crop (modules) + 3.75 $kgCO_{2-eq}$/crop (growing systems) = 6.10 $kgCO_{2-eq}$/crop. This is a reduction of 6.10 $kgCO_{2-eq}$/crop ÷ 25.95 $kgCO_{2-eq}$/crop = 23.51%. Based on that, it can be concluded that the applied improvements are justified and proved to work.

table 14: subtotal carbon footprints resulting from constructing modules and growing systems (own, 2023)

module	MightyVine phase 3		8T4B module configuration	
	#	footprint (total)*	#	footprint (new)*
 trellis-link corner	2	28,978	4	29,078
 endwall	26	250,199	12	63,275
 transition sidewall	2	13,110	4	11,244
 full-pane sidewall	47	298,224		
 transition midfield	26	70,785	12	7,799
 full-pane midfield	611	1,651,986	0	
endwall bracing	4	73	2	36
sidewall bracing	4	371	2	185
midfield bracing	52	7,720	7	1,039
deck bracing	54	823	14	213
center aisle	1	208,202		
 single system			88	180,587
 coupled system			82	296,862

* *all absolute carbon footprints are given in kgCO*$_{2-eq}$

reflection

The carbon footprint per crop of hybrid urban vertical farming is 163% that of greenhouse agriculture. That means that, in terms of material use, hybrid urban vertical farming is not yet a sustainable alternative to conventional farming practices. However, the hybrid urban vertical farm does have a 3.3 times higher footprint utilization. In a time where there is not enough farmland available to build greenhouses, vertical farming must be applied to grow more crops on a small footprint (p1 intro c2 sector). However, hybrid urban vertical farming may underperform greenhouse agriculture, but it is more sustainable than vertical farming. Even in the more sustainable alternative scenario to conventional farming practices in p1 intro c2 sector, vertical farming had a 2.4 times higher $kgCO_{2\text{-eq}}kg^{-1}$ crop than (non soil-based) greenhouse agriculture. This unit differs from $kgCO_{2\text{-eq}}$/crop, but as long as the units remain the same within comparisons (within p1 intro c2 sector and within p6 carbon c3 compare), the deviations expressed in factors can be compared.

Vertical farming is 2.4 times less sustainable than non soil-based greenhouse agriculture, while hybrid urban vertical farming is 1.63 times less sustainable than greenhouse agriculture. As hybrid urban vertical farm growing systems are designed to reuse resources (water, nutrients, etc.), and in annually substitute one-third of artificial light (34%) can be naturally, it can be reasoned that hybrid urban vertical farming is more sustainable than vertical farming.

From that, it can be concluded that *hybrid* urban vertical farming truly is a *hybrid* farming practice. On the one hand, it has a smaller footprint per crop than greenhouse agriculture, but is less sustainable per crop. On the other hand, it has an equal/greater footprint per crop than vertical farming, but is more sustainable crop. Thus, hybrid urban vertical farming is a more sustainable alternative to vertical farming in the years up to and after 2050, when all farmland is in use or depleted. Until then, it is inferior to greenhouse agriculture.

By that time it will be irrelevant whether greenhouse agriculture is more sustainable than hybrid urban vertical farming; if there is no more farmland for greenhouse agriculture and open-field cultivation, the next best (most sustainable) farming practice is hybrid urban vertical farming (1.63 times less sustainable than greenhouse agriculture), and not vertical farming (2.4 times less sustainable than greenhouse agriculture). Until then the concept can be persistently improved to make hybrid urban vertical farming competitive with conventional farming practices sooner. **Until then, it is up to the grower to decide what is important: higher yields per square meter, or a low carbon footprint per crop.**

The research conducted in this chapter has been incorporated in the design of a hybrid urban vertical farm. Now, at its conclusion, references are made to the chapters in which the features identified as important in this chapter have been incorporated into the design.

- The carbon footprint per crop of the case study MightyVine phase 3 and an 8T4B hybrid urban vertical farm module configuration is the premise of the conclusion (p8 conclusion c1 conlcusion).

compare

The research in each part is conducted to answer one or more sub-research questions, which will ultimately help answer the main research question. These sub research questions are answered by means of a certain product, identified in p1 intro c3 research. The results are discussed here.

In p6 carbon one sub research question has been answered, the seventh one. The question and the approach to finding an answer to it were:

7. Regarding the aspect "sustainable, and economically feasible": "*How much emissions are saved when building a farming system with reused components?*". It is answered in p6 carbon by means of a carbon footprint calculation of the construction of the optimal hybrid urban vertical farm and its growing systems **and** a carbon footprint calculation of the construction of a case study greenhouse **and** a comparison of the carbon footprint per crop of a hybrid urban vertical farm and a greenhouse;

This question is answered in c3 compare. To provide a concise answer to this question, a summary of the conclusion of the carbon footprint calculation is given below:

The carbon footprint per crop of greenhouse agriculture, calculated by means of the case study MightyVine phase 3, is 3.75 $kgCO_{2\text{-eq}}$/crop. To save emissions per crop in a new farming practice, hybrid urban vertical farming, its emissions per crop should be lower. However, the carbon footprint per crop of hybrid urban vertical farming, calculated by means of the optimized 8T4B module configuration, is 6.10 $kgCO_{2\text{-eq}}$/crop. Thus, no emissions are saved when choosing hybrid urban vertical farming as an alternative farming practice over (non soil-based) greenhouse agriculture, instead the emissions increase by a factor 1.63.

As vertical farming has a 2.4 times $kgCO_{2\text{-eq}}kg^{-1}$ crop than greenhouse agriculture (p1 intro c2 sector; (Blom et al., 2022)), it can be concluded that hybrid urban vertical farming truly is a hybrid farming practice: in both footprint utilization and the carbon footprint per crop it sits between greenhouse agriculture and vertical farming.

Since vertical farming is 2.4 times less sustainable than greenhouse agriculture, it can be concluded that hybrid urban vertical farming is really a hybrid farming practice: it lies in between greenhouse agriculture and vertical farming in terms of both footprint use and carbon footprint per crop.

So, concluding, when available farmland runs out by in the years up to 2050, emissions can be saved by choosing hybrid urban vertical farming over vertical farming. The exact amount of emissions that can be saved cannot be calculated because the comparative studies of (Blom et al., 2022) and this thesis took a different approach to calculate the carbon footprint per crop. However, based on the deviation factors that express how many times less sustainable hybrid urban vertical farming and vertical farming agriculture are compared to greenhouse agriculutre, it is reasoned that hybrid urban vertical farming (deviaiton factor of 1.63) is a more sustainable, less emitting farming practice than vertical farming (deviaiton factor of 2.4).

A better approach for comparing the carbon footprints of conventional farming practices and hybrid urban vertical farming is addressed in the discussion.

part seven

integration

p7 integration

in this part

In p7 integration, ways are found to make hybrid urban vertical farms more sustainable by increasing the cirucularity of the resources they use. If greenhouses themselves were more circular, this would affect the construction of modules. How the greenhouse construction industry can become more circular is covered in c1 greenhouses. Then it is time to look at resources. The research in this thesis so far has focused on the materials of building modules and growing systems. But those systems, in those modules, need resources such as water, nutrients, CO_2, etc. to grow crops. Today, most resources in horticulture come from finite sources, but as the entire world moves toward a fully circular economy, it is time in c2 resources explore how greenhouses and hybrid urban vertical farms can replace the finite resources they currently use with renewable versions - preferably from urban and industrial sources, as these will be located near the hybrid urban vertical farms. Finally, c3 urban sketches a way to integrate a hybrid urban vertical farm into a familiar urban environment, as a way to show how the new farming practice can invite, intrigue, and reap the benefits of not only material, but also human knowledge.

c1 **greenhouses**

c3 **resources**

c4 **urban**

in this chapter

Greenhouses, and hybrid urban vertical farms, can become more sustainable door meer deel uit te maken van een circulaire economie. To reflect on what can be improved, this chapter discusses greenhouse details, the current degree of circularity of the sector, the lifespan of greenhouses and their components, and the (innovations in) material use.

individual greenhouses

In p2 reuse c2 circularity a preview was already given on one of the main circularity features of greenhouses. The rule: **do not weld on the construction site.** That is why all welded components are finished in the factory. That rule was clarified by means of a midfield column - trellis - gutter detail. This is a good a good example of how individual greenhouses are fully circular and demountable. A similar detail, now of a gable, is shown in *figure 68*. Again, the individual parts (gable column with purlin corners, purlin, aluminum rods, glass panes, and rubbers and PVC strips) are completely disassemblable. But, just like welded midfield columns and trellises, a gable column must always be rebuilt with purlin corners to support a new purlin, so it does not matter that the purlin corners remain welded to it.

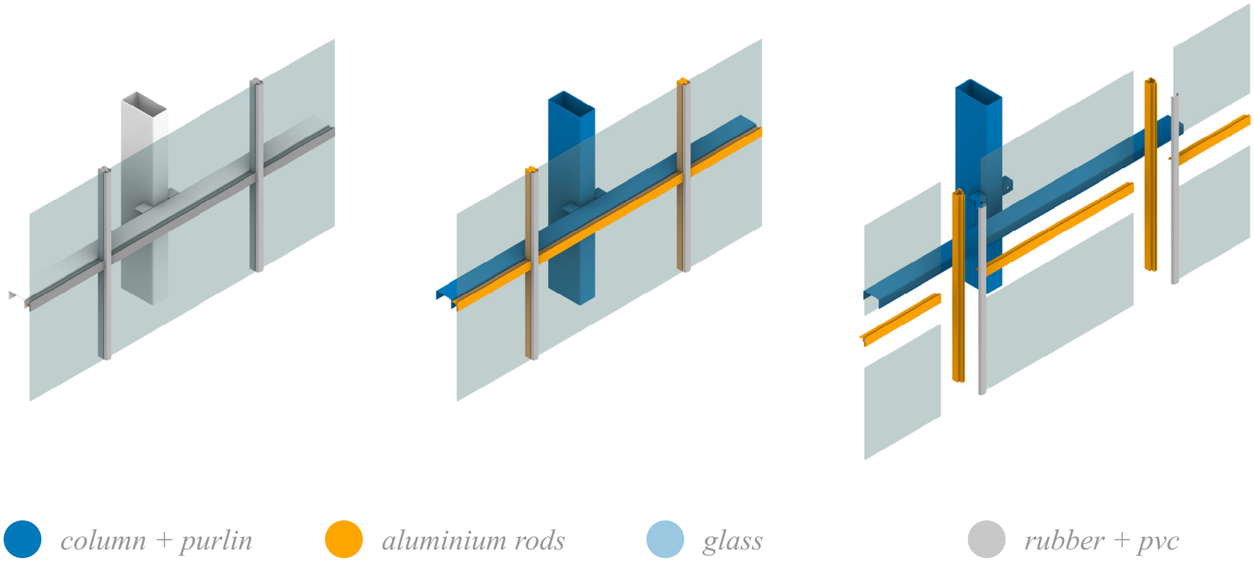


figure 68: circularity and demountability of connected welded steel components (own, 2023)

development of the sector

In the past traditional steel AP steel gutters were used in greenhouses. They varied in height only to accommodate regions of varying precipitation, and simple aluminum rods fit on those. Then, a grower could buy rods from another grower to use as replacents for his own (van der Knijff, A. [Handelsonderneming A.C. van der Knijff B.V.], personal communication, December 10, 2022). Today, aluminum can be produced by extrusion machines to fit individual greenhouses and their steel structure. VB can have various gables/ decks customized (e.g., connection holes) by informing BOAL about the design parameters. This way, VB's greenhouse is optimally strong and light weight. However, those parts can not connect to parts of other greenhouses. Thus, the far-reaching customization of aluminium gables and decks compromises the sector's overall circularity.

restructuring

The world's densest horticultural area, het Westland, in the Netherlands, has seen a large-scale restructuring of greenhouses in the past decenium that is still going on. In 2013, the average size of 1,393 greenhouses there was under 2 hectares with a total area of 2,677 hectares. Nowadays, the desired size of a greenhouse for flowers is 3-6 hectares and for vegetables in bulk 5-30 hectares. Therefore, greenhouses are demolished and larger ones are built outside the urban borders. America experiences a similar trend (Onder Glas, 2016). Another trend is the expansion of urban areas to meet the growing demand for urban housing. To this end, growers are being bought out, after which greenhouses are being demolished and residential areas rebuilt.

lifespan

The technical lifespan of a greenhouse is estimated at 15 years, the reasons for that are (Onder Glas, 2016): First, the technical life is based on the expected life of the greenhouse's materials. While some greenhouses may be made of materials that last longer than 15 years, such as tempered glass, the use of other materials, such as polycarbonate and plastic, can shorten the lifespan of the greenhouse. Second, over time, greenhouses may experience wear and damage due to external factors such as severe weather conditions, improper use, aging and lack of maintenance. This can lead to repair costs that at some point are no longer economical, and it can become difficult to find replacement parts. Third, greenhouse technology is constantly evolving and new materials and techniques improve the efficiency of greenhouses. Therefore, after 15 years, it may make sense to consider replacing a greenhouse with a newer, more efficient and durable model better suited to new requirements and conditions.

However, a greenhouse can last for four decades when properly maintained. The lifespan is matched to the material with the least longevity; steel and aluminum can be used even longer. This is based on the experience of a greenhouse designer at VB (for over 30 years) and has seen how long it takes greenhouse owners to have a new greenhouse built (M. van Leeuwen [VB], personal communication, May 10, 2023).

table 15: lifespan of greenhouse components compared to a complete greenhouse (own, 2023)

Component [-]	Lifespan of component [year]	Relative lifespan compared to a complete greenhouse [%]
Complete greenhouse	15	100%
Steel structure	80	533%
Aluminium profiles	60	400%
Glass panes	25	167%

Table 15 shows the lifespan of materials relative to the greenhouse. In a well-maintained greenhouse all main 1components are reusable because their lifespan exceeds the demolition date. Is is acceptable if some new parts have to be used, as that does assure that components with a longer longevity can also be reused. When, first, small greenhouses are demolished to build larger ones, and second, greenhouses within urban expansion areas are demolished for housing development, reusable components can be reclaimed to build of hybrid urban vertical farms. These can be integrated in (newly developed) urban environments.

This data, which show that the lifespan of steel and aluminum in particular is many times longer than that of a complete greenhouse, prompted the research in this thesis. Of course, steel and aluminium (and glass) can also be melted and recycled, but much more energy is lost in that process than in direct reuse.

new materials

In industries other than greenhouse construction, new materials are being experimented with that are more durable or have properties that can make the process in which the material is used more sustainable. In this chapter magnelis steel and fibre reinforced plastic foundation slabs introduces, these are both innovations on today's two most uncircular main greenhouse materials.

Steel is normally protected from corrosion by hot-dip galvanizing it in 450 ºC liquid zinc. The molten zinc alloys with iron in steel creating a protective layer. Hot-dip galvanizing has three disadvantages: first, steel joints must be welded before galvanizing, because welding galvanized steel releases pollutants (health hazard), second, grinding galvanized steel joints releases pollutants, so a respiration mask must be worn during disassembly, and third, reclaimed steel must be dezinced before it can be welded and galvanized again. Reclaimed steel can be welded immediately, then the ungalvanized surfaces must be treated with zinc spray. That is a faster, more durable microsolution alternative than dezincing - welding - galvanizing.

There is an alternative to hot-dip galvanizing: a Magnelis coating that protects steel surfaces ten times better than a zinc coating. A Magnelis coating consists of zinc alloyed with 3.5% aluminium and 3% magnesium. The magnesium ensures that steel is protected from corrosion for up to 25 years. Magnelis is self-healing on grinded edges (ArcelorMittal, n.d.). Other advantages of Magnelis over hot-dip galvanizing are its excellent workability when welded, the environmental friendliness of the coating because Magnelis contains less zinc than a normal zinc coating, and the price is lower because the protection is now formed during steel production rather than in a separate galvanizing process. Magnelis RHS sections are shown in *figure 69*.

figure 69: magnelis RHS sections (l) and the variety of available magnelis profiles (r) (own, 2022).

Because Magnelis steel can be welded when *already* protected against corrosion and recovers itself where it has been grinded, it can be welded elsewhere immediately after a greenhouse is dismantled. Thus, the reuse of Mangelis steel skips several stages compared to the reuse of hot-dip galvanized steel. Three reuse processes are illustrated and annotated in *figure 70*. In addition to the standard reuse of hot-dip galvanized steel (top), the microsolution variant is also illustrated in which grinded steel is treated with a zinc spray before it is re-welded (middle). However, as mentioned, this variant requires compliance with health protection measures.Skipping the dezincing - welding - galvanizing stages saves energy and the carbon footprint associated with that energy use. The galvanization of one kilogram of steel requires 3.4 - 5.3 MJ of energy, equal to a global warming potential of 0.1 – 0.33 kg CO_2-equivalent emissions (Galvanizeit, n.d.).

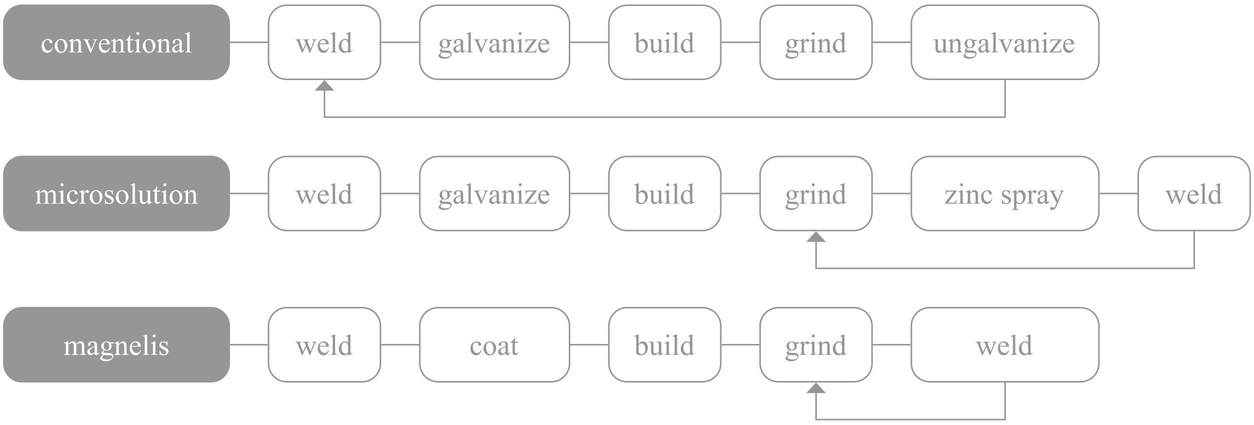


figure 70: reuse processes of hot-dip galvanized steel and magnelis steel (own, 2023)

fibre reinforced foundation

The gables of MightyVine phase 3 rest on a monolithic poured foundation beam that rests on foundation piles, both of which are not reusable because they cannot be removed from the ground in their entirety. Other greenhouses use more elegant foundations consisting of concrete dollies every few meters (*figure 71*, left) with a notch into which concrete slabs are placed (*figure 71*, center). When greenhouses with these types of foundations are demolished, the concrete is often not reused because it is too damaged and because the long slabs are difficult to remove from the ground, transport, etc.

figure 71: concrete dollies (l), concrete slabs (m), and fibre reinforced slabs (r) (own, 2023)

An alternative are fibre-reinforced slabs (*figure 71*, center) that are made of reinforced recycled plastic and can be recycled themselves. These plastic slabs are as strong as concrete slabs and do not deteriorate faster, but their light weight makes them easier to disassemble and reuse.

in this chapter

A hybrid urban vertical farm reuses greenhouse components. However, there are more strategies to make the horticultural sector circular; there are numerous ways to narrow, slow, and close the loop of resources needed to grow crops, as well as ways to substitute a finite resource in the loop with a renewable one. Strategies for better use of water, nutrients, substrate, CO_2, biomass, plastics, and heat are discussed.

water

Water that is not absorbed by crops in a hybrid urban vertical farm is diverted back to the irrigation room so it can be reused. Recirculation *narrows* the loop because less new resources (water) are used.Runoff water contains sodium that can accumulate around roots and decrease nutrient absorbtion and growth of crops. Sodium can be captured by treating runoff water with NoNa$^+$, this way runoff water does not have to be discharged due too unacceptable high sodium concentrations and unabsorbed nutrients are not wasted (Ridder, n.d.). Using NaNo$^+$ *closes* the loop because less waste (discharged runoff water) is generated.

Even if excess sodium is captured, a source of freshwater is still needed. Instead of freshwater sources, like groundwater, treated sewage and industrial wastewater from treatment plants can be used (*figure 72*). Using treated wastewater is a *substitution* in the loop because finite resources (fresh water sources) are replaced with renewable resources (wastewater treatment plants) (Onder Glas, 2020). Even more sustainable is to increase the rainwater storage of a farming system. Because water evaporates through crops and becomes available to the outside air through windows, it is a renewable source. It decreases the need to deplete freshwater sources. Increasing rainwater storage is a *substitution* in the loop because finite resources (fresh water sources) are replaced with renewable resources (rainwater storage).

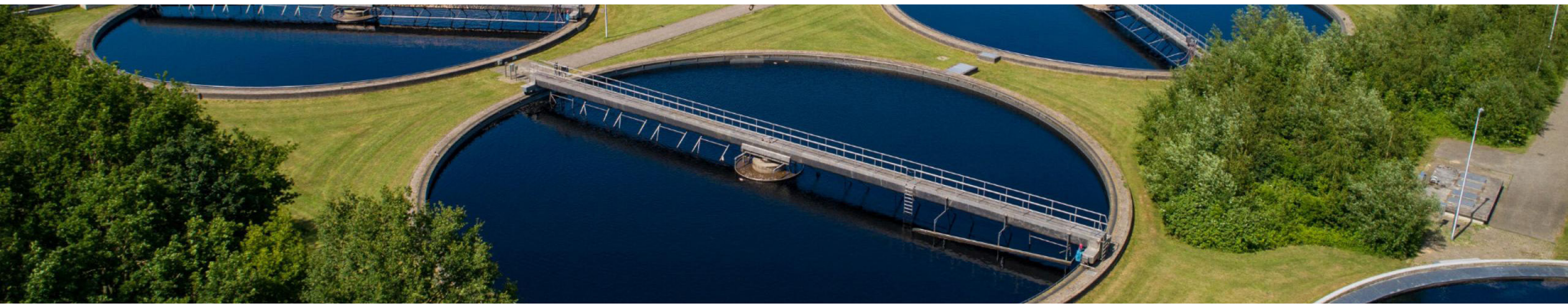


figure 72: wastewater treatment plant, a renewable water source (Drents Overijsselse Delta, n.d.)

nutrients

Besides preventing dicharge of unabsorbed nutrients by treating runoff water with NaNo+, the number of unabsorbed nutrients can be reduced by better studying which macroelements are used per type of crop and feeding only those dosed after study. Specific deployment of macroelements *narrows* the loop because less new resources (nutrients) are used (Glastuinbouw Waterproof, 2019).

substrate

The best approach to use substrate more sustainably is to stop using it and cultivate crops in hydroponic, aeroponic, or aquapoinic systems that do not need substrate. Stopping the use of substrate in a growing system *narrows* the loop because fewer new resources (substrate) are used.

To improve the end-of-life scenario of substrate it can be a primary resource for bricks or other building products. Substrate can be used for only one growth cycle, after that it has an increased risk of disease and a decreased functionality (Royal Brinkman, n.d.). Using substrate waste as a primary resource in other industries *narrows* the loop because fewer new resources (primary resources in other industries) are used.

co$_2$

CO_2 is used dosed in a greenhouse to increase crop growth (and production). Most CO_2 is produced with fossil fuels. There are growers that decide to equate indoor and outdoor cultivation; they stop adding CO_2 and use the natural concentration in outdoor air. Adding less/no CO_2 *narrows* the loop because fewer new resources (CO_2 from fossil fuels) are used. CO_2 concentrations can be increased by supplementing it with CO_2 from *direct air capture* (DAC) technologies that capture CO_2 from outdoor air. Another option is to use CO_2 that is created as a by-product at industrial plants, such as the OCAP CO_2 pipeline in the Netherlands which, among others, distributes CO_2 produced at Alco's bioethanol plant (OCAP, n.d.). Using DAC or OCAP is a *substitution* in the loop because finite resources (CO_2 from fossil fuels) are replaced with renewable resources (outdoor air or by-product).

biomass

Plant residues (e.g., stems and leaves) can be used as primary resource in the biofuel industry. Biomass can also be circulated within the horticultural sector; for example, phosphate ore and potash from plant waste can be composted into fertilizer. Using fertilizers from plant waste is a *substitution* in the loop because finite resources (minerals/ore) are replaced with renewable resources (plant residues).

plastics

Plastic is widely used as a packaging material, but the plastic footprint of crops goes beyond the packaging of a finished product. Much plastic is also used in the cultivation process, all of which is made from finite primary resources: crude oil and natural gas. Many plastic elements are being replaced by metal versions. For example, in high-wire cultivation like tomatoes, peppers, cucumbers, and eggplants, the plastic wires wrapped around stems are replaced by metal clips (Pelikaan, n.d.). Another example is the replacement of plastic clips that support the connection between a vine of tomatoes (or any other crop that grows in bunches) and the main stem. These clips ensure that produce does not collapse under its own weight. Both metal variants can be reused after disinfection without loss of strength, while plastic variants must be replaced after a season or two of weakening under UV-light. Replacing plastic parts with metal versions *narrows* the loop because fewer new resources (less plastic) are used. Another improvement in the plastic footprint is the increased use of recycled plastic in, for example, gable and soil films. Use of recycled plastic *closes* the loop because less waste (plastic) is generated.

heat

The biggest transition in making horticulture heating circular is connecting farming practices to geothermal networks. VB, among others, has built several geothermal heating plants in recent years. One of them, Green Well Westland, made sustainable energy available to the 40 hectares of greenhouses. Used, cooled water is pumped (cleaned) back into the Earth to be reheated. Using geothermal heat is a *substitution* in the loop because finite resources (heat from fossil fuels) are replaced by renewable resources (geothermal heat) (Arnaud Blom [VB], personal communication, February 9, 2023).

in this chapter

The design of hybrid urban vertical farms is already quite circular, many of the components for the construction of modules are reused, and non uptaken resources are recycled in the growing systems; through the draining profiles, drained water with nutrients returns to a technical room where it can be reused. The previous chapter listed ways to substitute finite resources with renewable ones from the urban/industrial environment. In this chapter, some socioeconomic factors are added, supported by an illustration showing how a hybrid urban vertical farm can be placed in a recognizable location where it can utilize resources (material and human) for higher circularity and better integration.

urban integration

There is a variety of ways that hybrid urban vertical farms can stimulate the engagement of local people in the goings-on of the farm. Some examples in the areas of social interaction, employment, education, cultural exchange, and research include (Yuan et al., 2022):

Social interaction: hybrid urban vertical farms can organize farmers's markets where local residents can shop for fresh produce. This creates a platform for community members to engage with local farmers, learn about sustainable farming practices, and support the local food system;

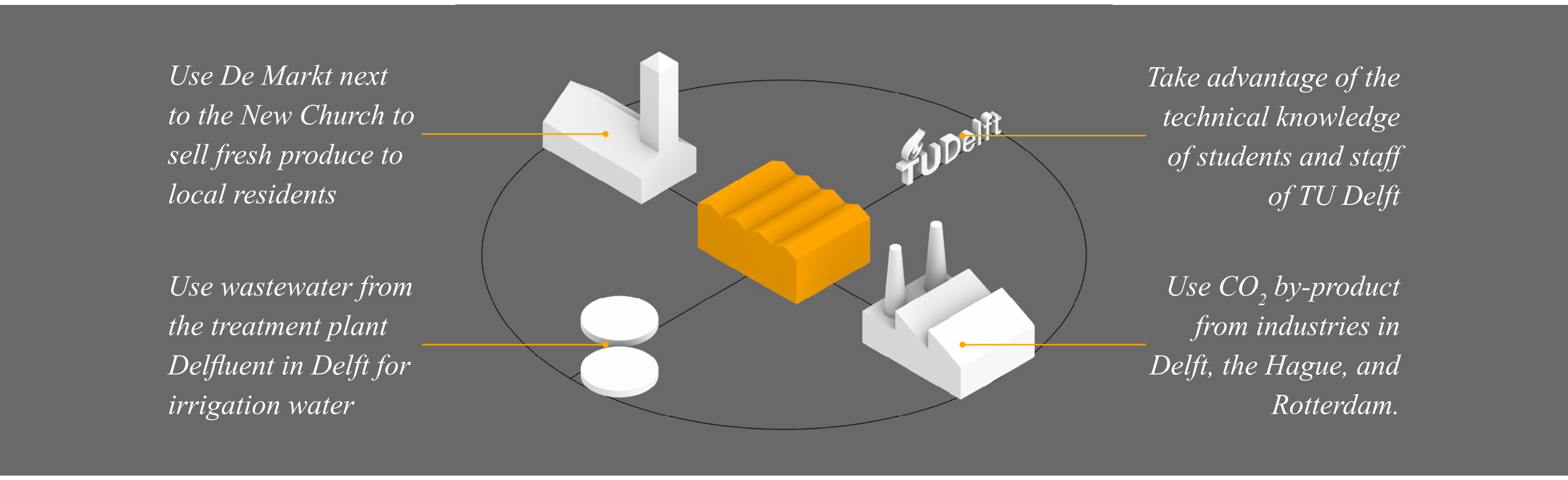
Job provision: hybrid urban vertical farming can generate employment opportunities, particularly in economically disadvantaged neighborhoods. By training and hiring local residents, urban farming initiatives can help reduce unemployment and contribute to the economic development of the community;

Education: hybrid urban vertical farms can serve as learning centers, organizing workshops, training sessions, and demonstrations to share knowledge about sustainable farming practices. This stimulates knowledge exchange among farmers, researchers, and the community, contributing to the growth of urban agriculture. Teaching about urban farming in schools and community centers can educate people, especially children, about sustainable agriculture, nutrition, and environmental entrepreneurship. This can equip individuals with valuable skills for future employment and healthy living;

Cultural exchange: community markets can serve as a gathering place for diverse communities, creating opportunities for cultural exchange and celebrating culinary traditions. This fosters social integration, promotes diversity, and strengthens community bonds. This can also lead to the diversification of crops grown in different farms to suit different cultural food preferences.

Research and education: community markets can host educational events such as workshops, demonstrations, and guest speaker sessions to raise awareness about closed-system urban farming. This enables residents to learn about sustainable practices, local food systems, and the environmental benefits of urban agriculture. This way, besides stimulating the development of hybrid urban vertical farms, there will also be greater awareness of the need for agricultural R&D to increase the efficiency of food production in the years up to and beyond 2050 (as was deemed important in p1 intro c1 food threats).

Figure 72 shows how a hybrid urban vertical farm in Delft can be the center of socioeconomic urban exchange and use renewable resources from urban and industrial processes in the city.



Use De Markt next to the New Church to sell fresh produce to local residents

Use wastewater from the treatment plant Delfluent in Delft for irrigation water

Take advantage of the technical knowledge of students and staff of TU Delft

Use CO_2 by-product from industries in Delft, the Hague, and Rotterdam.

figure 72: urban integration of a hybrid urban vertical farm in Delft (own, 2023)

architecture

As was discovered in p5 optimize c3 columns, an 8T4B module configuration is the most efficient in terms of reuse percentage of components of MightyVine phase 3. This configuration has a lenght of 72 meters and a depth of 18 meters. That sounds big; to put the size in perspective with a familiar building, *figure 73* shows how this module configuration (orange) fits on the parking lot of the Faculty of Architecture at Delft University of Technology (white). It may be assumed that by 2050 there more cars will be shared among people, and thus some space will become available in the parking lot. A 3D model with volumes shows that a hybrid urban vertical farm is not that big compared to the faculty building; the Bouwpub can even remain in place untouched. Lettuce, and similar crops (radishes, swiss chard, arugula, spinach, gren beans, cucumbers, zucchini, beets, turnips, kohlrabi, etc.) have a growing time of about 8 weeks. If the 98,768 crops that can grow in the module configuration are planted evenly over time, 1,764 crops can be harvested every day. That should be enough to supply the university canteens with vegetables, and sell the rest to local residents at Delft markets on Tuesdays (Papsouwselaan), Thursdays (de Markt and Brabantse Turfmarkt), and Saturdays (Branbantse Turfmarkt and Burgwal), or at a self-organized farmers' market.

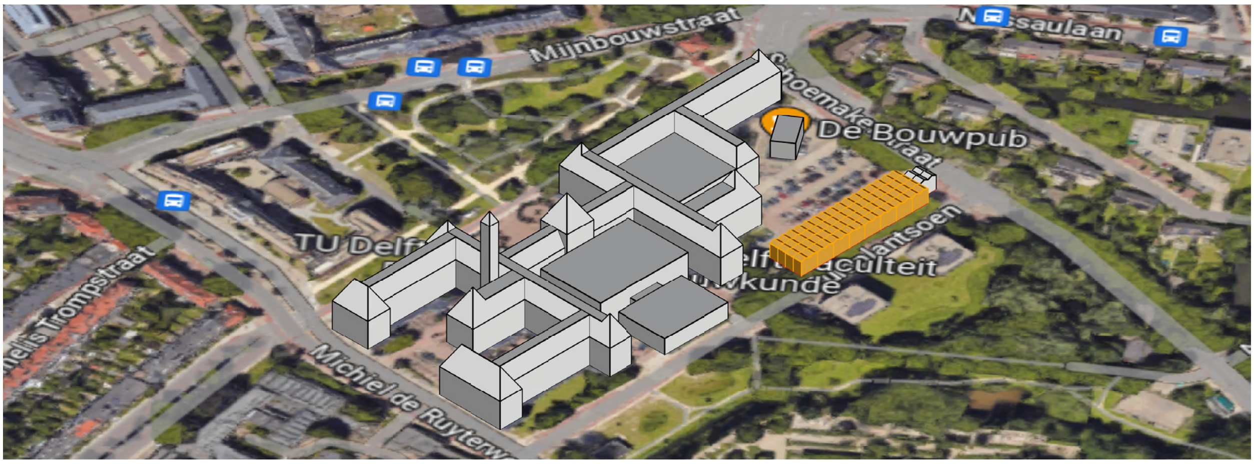


figure 73: an 8T4B module configuration on the parking lot of the faculty of Architecture (own, 2023)

The research in each part is conducted to answer one or more sub-research questions, which will ultimately help answer the main research question. These sub research questions are answered by means of a certain product, identified in p1 intro c3 research. The results are discussed here.

In p7 urban two sub research questions have been answered, the eight and nineth one. The questions and the approach to finding an answer to it were:

8. Regarding the aspect "urban modular farming,": *"How can urban farms connect to and utilize urban infrastructure and facilities?"*. It is answered in p7 integration by means of an overview of ways to substitute finite resources by renewable resources **and** an overview of ways to integrate a (hybrid urban) vertical farm with the socio-economic facilities that an urban infrastructure has to offer.

This question is answered in c2 resources and c3 urban. To provide a concise answer to this question, a summary of the ways to integrate a hybrid urban vertical farm in the urban environment is given below:

First, hybrid urban vertical farms (and horticulture in general) can become more circular by using renewable resources generated in urban and industrial processes. Reusing water, nutrients, substrate, CO_2, biomass, plastics and heat can substitute finite resources with renewable ones, making the sector more circular. Second, the socioeconomic facilities of the urban environment can be taken advantage of: hybrid urban vertical farms can host farmers' markets where local residents can meet, learn about sustainable agriculture and share cultures. In addition, hybrid urban vertical farms can provide job opportunities and reduce unemployment while encouraging economic development in communities. Third, hybrid urban vertical farms can serve as learning centers for the community to learn about the need to grow food sustainably, as well as a reminder that yields per square meter need to get higher in order to produce enough food by 2050.

9. Regarding the aspect "sustainable, and economically feasible": *"How can greenhouses be designed more modular to better enable future reuse?"*. It is answered in p7 integration by means of a reflection on on the circularity of individual greenhouses, and greenhouse construction as a whole.

This question is answered in c1 greenhouses. To provide a concise answer to this question, a summary of the conclusion of the carbon footprint calculation is given below:

Individual greenhouses cannot become much more circular in terms of their construction, which is already fully dismantleable. However, it seems that the greenhouse construction sector as a whole has become irreversibly uncircular. Greenhouses today are so high-tech and so optimized per site because the producers of greenhouse components (especially aluminum) offer opportunities for this through far-reaching customization. Greenhouse designers (such as VB) are used to this and will not accept reduced customization opportunities, especially since the ever-expanding greenhouses (5-30 hectares for vegetables) are such large orders of material that it is also no longer less profitable for steel and aluminum suppliers to deliver a customized product for each customer; economies of scale are already being achieved within a greenhouse. This is completely reversed from the past, when only a limited number of gutters and gable and deck systems could be exchanged between multiple greenhouse owners.

part eight

conclusion

p8 conclusion

in this part

In p8 conclusion, an answer to the main research question is given in c1 conclusion. This answer is based on the answers to the sub research questions, that have already been adressed after the previous parts of the report. In c2 disucssion recommendations for further research are made, and in c3 reflection some academical reflection on the research done is given first, followed by a personal reflection on the graduation period.

c1 **conclusion**
c2 **discussion**
c3 **reflection**

in this chapter

After completing the research in this thesis, the main research question can be answered. For that, the answers and conclusions to the sub research questions on the last page of each part are used.

main research question

The main research question that was formulated at the start of this thesis is: "*How can a modular hybrid urban vertical farming practice be constructed with reused greenhouse components, and become high yielding, sustainable, and economically feasible?"*

answer

A modular hybrid urban vertical farming system, called *hybrid urban vertical farming*, can be constructed with reused greenhouse components. To do this, a greenhouse that is to be demolished must be divided into a grid within which the steel structure is repeating. This is a grid of one trellis wide and one bay deep. A hybrid urban vertical farm built from reused components must maintain an equal or a smaller grid of the greenhouse from which components originate. An equal grid ensures that components produced to fit together exactly will fit together again in a redesign/rebuild. In a smaller grid, components can be shortened to still fit together. Because existing parts cannot be extended, rebuilding in a larger grid is not possible.

A hybrid urban vertical farm can be high yielding by growing crops in the designed sliding and rotating growing system. An 8T4B module configuration has a 3.3 times higher number of crops/m^2 compared to greenhouse agriculture. Single and coupled growing systems hold, respectively, 16 and 32 containers containing 24 crops. Because the growing system is mounted on sliding rails, only one workspace is needed between multiple growing systems, unlike conventional farming practices where there is a workspace next to every growing system. As a result, the relative amount of workspace is low, and the relative amount of crops per m^2 is high. In addition, it is recommended to build a module configuration with an even number of bays deep (so that 75% of the depth is utilized for placing growing systems) and as many trellises as the available reusable components allow (so that the relative amount of sidewall space remains low).

A hybrid urban vertical farm becomes sustainable by, first, reusing components for the construction of modules and growing systems so that the carbon footprint of the farm is lower than when built with new components. Second, by using a rotating growing ssytem and utilizing 34% daylight on annually and saving on electricity for artificial lighting. Third, by applying only the minimum required number (nine) of artificial lights to saturate the light requirements of crops.. Fourth, by building an 8T4B module configuration to reuse as many components as possible (95% of the midfield columns). A hybrid urban vertical farm is less sustainable than greenhouse agriculture (1.63 times less sustainable), but more sustainable than vertical farming (which is 2.4 times less sustainable than greenhouse agriculture). This means that when farmland runs out in the years up to 2050, hybrid urban vertical farming is more sustainable than vertical farming.

Hybrid urban vertical farming saves money by, first, dimming artificial light at times when crops do not need them at 100% power (all weeks but the week around December 21), thus saving money on electricity, and second, building an 8T4B module configuration so that as many reclaimable components can be reused, and money is saved on buying newly manufactured components. Unfortunately, no research has been done on the economical feasibility, this is addressed in p8 conclusion c2 discussion.

discussion

in this chapter

The research in this thesis answered the main research question, as seen in the conclusion. However, a number of new questions also emerged that can be answered in future research.

irrigation

As mentioned in p4 system c3 design, the discussion would adress follow-up research on flexible irrigation hoses. How containers are irrigated, and how non uptaken water can be reused has been addressed. However, how a sliding growing system can stay connected to a water supply has been left out of consideration as to not focus this thesis too much on the details of the growing system. There are hoses that can stretch by 1,500 mm (the minimum stretch length required; this is the workspace between growing systems). To make sure that the irrigation design of growing systems works in practice, it would be wise to have a climate company look at it, which can also calculate the hose diameters for sufficient irrigation supply.

lca analysis

As mentioned in the answer on sub research question 7 in p6 carbon, the discussion would adress a better approach for comparing the carbon footprints of conventional farming practices and hybrid urban vertical farming. In this thesis, the carbon footprint per crop was determined by calculating the emissions released during the production of materials needed for the construction of modules and growing systems. Those results are compared with the results of a study on the carbon footprint per kilogram of produce for the four conventional farming practices (open field cultivation, greenhouse agriculture (soil-based and non-soil-based) and vertical farming) (Blom et al., 2022). However, that research includes upstream stage, core stage, and end-of-life stage of both the farm and crops. In comparison, the research in this thesis only looks at upstream stage of the farm. To better compare how hybrid urban vertical farming compares to conventional farming practices, a carbon footprint analysis should be conducted similar to the approach taken by Blom et al (2022). Only then could a direct comparison reveal whether hybrid urban vertical farming is more sustainable than vertical farming, rather than drawing that conclusion by comparing anomalous factors relative to greenhouse farming.

(un)galvanization

Growing system reuse midfield columns by cutting them into verticals, arms, and feet. Midfield columns are galvanized and in greenhouse construction, grinding of galvanized steel is frowned upon. According to van der Knijff, it can be done as long as a proper dust mask is worn and grinding dust is extracted, and exposed surfaces are treated with a zinc spray or paste (van der Knijff, A. [Handelsonderneming A.C. van der Knijff B.V.], personal communication, December 10, 2022). This is a microsolution that is proven daily at van der Knijff's, but skepticism from the industry is no less. Follow-up research could address a more sustainable method of dezincification and rezincification at the demolition or construction site, so that transportation to a galvanizing plant can be avoided. Research could address the use of magnelis, which is a metal whose composition naturally protects it from corrosion even better than normal galvanized steel has.

practice test

To test if the growing system is stable (testing the paternoster system), receives enough daylight (testing the rotation principle), and gets enough supplemental light with nine artificial lights (testing the light intensity on containers at the bottom of the growing system) the system must be built in practice.

VB has expressed interest in building a single system. Building a design in practice reveals problems (and solutions) that might not have been addressed in this thesis. Building a growing system can increase the viability and potential of a hybrid urban vertical farm, or decrease it if it turns out not to work in practice.

light simulations

The light simulations were performed with a sophisticated software tool (Grasshopper/Ladybug), but the density of the test grid was not set as high as possible because the author does not have a computer capable of handling such simulations. It is advisable to redo simulations with a denser grid, as this can change the intensities of received daylight (the author has worked with four densities, and the results do not always get better with a less dense grid, and vice versa do not always get worse with a denser grid). It is also advisable to run the simulations also with other (professional) software to see if the results match and thus are valid.

economic feasibility

This thesis had researched the feasibility of hybrid urban vertical farming by means of a carbon footprint analysis. However, in order to be able to conclude wether the concept really has potential, the economic side of things must also be considered. To determine if the concept is economically feasible, research should be done on the cost of demolition and rebuilding compared to building a hybrid urban vertical farm with new parts. If the cost of demolition and rebuilding is significantly higher than the cost of building a hybrid urban vertical farm with new parts, reuse may not be economically feasible. In addition, it must be investigated whether the cost saved for artificial lighting outweighs the cost of building a rotating growing system. If both studies show that a hybrid urban vertical farm is not economically feasible, then despite hybrid urban vertical farming being a more sustainable farming practice than vertical farming, it is not a competitive alternative to existing farming practices in terms of finances. Again, VB expressed interest in doing a price analysis of a single system.

installations

Because crops in a rotating growing system do not get overexposed by sunlight (they get a maximum of 63% of their desired photosynthetic photon flux density (PPFD) during the week around June 21 in a zero configuration), no light screen is integrated into the construction of the modules. However, many growers do prefer a climate screen; this allows transmission of PAR light but blocks infrared light that heats up the greenhouse. In addition, there are also rules for urban farms to have a screen that blocks light pollution in the evening and night. A follow-up study by a climate company can look at what screens are needed in a hybrid urban vertical farm, and how those screens affect the carbon footprint.

technical room

All calculations in this thesis are based on the premise that growing surface is compared to growing surface. The proportion that storage and technical room have in the footprint of both a greenhouse and a hybrid urban vertical farm is excluded. However, that attached space is needed for piping, energy systems, heat pumps, storage, possible offices, etc. If a hybrid urban vertical farm were to be built, it is important to determine how large the attached space should be to accommodate these functions. Such a space does not have to be architecturally interesting, but it can be because it will be built in the urban environment. The greenhouse industry has years of experience in designing and constructing buildings attached to greenhouses, including connecting doors and the like.

case study (1)

The case study in this dissertation is a greenhouse with only one side wall because it was built against another greenhouse. It would be good to redo the entire study with a normal, self-contained greenhouse as case study to determine the extent to which a (different) case study affects the results. The presumption is that the presence of an additional sidewall, and thus twice as many reusable sidewall module components, does not significantly affect the optimize module configuration. An optimal module configuration is matched to the number of midfield columns; and these do not change in a greenhouse from the case study with four gables.

case study (2)

The case study, MightyVine phase 3, is a tomato greenhouse. However, for the purpose of comparing the crops per m^2 of a hybrid urban vertical farm and a greenhouse, that greenhouse is assumed to be a lettuce growing greenhouse. This is justified because the many lettuce greenhouses designed by VB have a similar construction. However, those greenhouses had somewhat untraditional floor plans, so the straightforward MightyVine phase 3 greenhouse was chosen. If the choice for a case study had to be made again, a lettuce greenhouse would have been selected for the sake of fair comparison. Then it could have been determined exactly how much lettuce could be grown in a one-layered system (whereas now 95% of the footprint has now been assumed). Follow-up research could use a lettuce greenhouse as a case study to recalculate crops per m^2 of greenhouse to make a fairer comparison with hybrid urban vertical farming.

c3

reflection

in this chapter

After completing the research in this thesis, the process and results can be reflected upon, this is done from an academical point of view first, and then from a personal point of view.

academical reflection

I reflect upon the academic value of my thesis by means of five questions:

1. *Did the chosen method prove to be the right one for this research?*

The research method that was chosen; combining literature review with practical research, and switching from design-by-research to research-by-design between p4 system and p5 optimize turned out to be a suitable approach for this thesis. Horticulture is a field about which little has been written or published online; most of the knowledge is kept within companies based in Westland. By working part time at VB, insights were gained into greenhouse construction. This allowed for complete designs and calculations. In addition, that position ensured that theoretical research from literature to be tested against practical views, preventing utopian designs, and making the designed modules and growing systems actually buildable. This method of research had a huge impact on the design, because the practical approach is the key to the design being buildable Conversely, the sceptical comments about design ideas that I derived from literature have caused them to either disappear or to be improved to be usable in practice (e.g., finding a micro solution to prevent the ungalvanizing/regalvanizing process).

2. *How did comments from mentors influence the thesis?*

Throughout my thesis, I received divergent feedback from my mentors. My first mentor ir. A.C. Bergsma (Architectural Engineering & Technology) encouraged me to focus on bringing attention to the circularity of the horticultural sector and suggesting improvements for increased circularity. I understood that feedback, and incorporated it into my thesis, but I personally felt that working out and improving the new cultivation concept hybrid urban vertical farming to design a higher yield/m^2 with lower energy consumption was more important. However, I found a balance in that, by considering in each improvement how it can contribute to a more circular greenhouse industry. Thus, mr. Bergsma's His recommendations made my research much more bipartisan than it would have been if I had fully implemented my own ideas about how to construct my thesis. However, I believe that if I had more time, I could do a better job elaborating on the sector's circularity, and in particular how to improve that circularity (which was also a comment after my P4 presentation).

My second mentor, Dr. A.J. Jenkins (Environmental & Climate Design), encouraged me to delve into existing vertical farming typologies at the beginning so that I would have knowledge of what I was going to attempt to improve. I found that difficult because I wanted to start designing right away. However, in retrospect I am grateful for his encouragement because it gave me a broad base and led directly to the new sliding and rotating culture system I designed. Before the study to existing vertical farming typologies I had never thought of a rotating typology. Having gained that knowledge also allowed me to have more interesting, engaging, and valuable discussions with Mr. Jenkins, leading to a better understanding of urban agriculture during the research. This made both the research and design more complete.

3. What is the academic and societal value and implication of the research, including ethical aspects?

I believe that hybrid urban vertical farming is a good alternative to vertical farming when there is no more farmland available to scale-up other conventional farming practices. As of now it is more sustainable than vertical farming, and by then hopefully developments will have made the concept even more sustainable. The high number of crops/m2 is promising. Because this research can be used as a steppingstone to a further improved and even more sustainable farming practice, I believe the societal value is high. After all, it is not a matter of *if* but a question of *when* farmland runs out and new farming practices are needed. After all, there must be a way to feed 10 billion people by 2050; starving a large number of them is not an option. That last remark expresses everything there is to say about ethics; except that the hybrid urban vertical farm can also bring communities closer together by jointly organizing a market, working, sharing knowledge, and culturally blending.

4. How transferable are the results of this thesis?

The approach to reusing greenhouse components, designing modules and growing systems with these components, and finding the optimal module configuration is the same for other greenhouses as for the case study. However, from greenhouses with a smaller footprint less components are reclaimable, so an optimal configuration will be smaller. This is not neccesarily a disadvantage, as most urban plots will be smaller than 72 by 18 meters (the dimensions of an 8T4B module configuration). Also, modules that are constructed from greenhouses that are less tall will not able to accommodate growing systems as tall as the modules constructed from MightyVine phase 3 components can accommodate. In those, the number of crops/m^2 will decrease rapidly. Thus, the method of design is 1-to-1 transferable, the yield/m^2 is not.

5. Why is it that the results in the P4 report were so much less positive than the final results?

First, during my P4, I presented modules that had a concrete floor. Greenhouse do not have a concrete floors, they only have a concrete center aisle: that is the first reason the modules hardly had a lower carbon footprint than a new greenhouse construction. Concrete has a relatively low production factor, but because it occurs in such large volumes it has a big impact on the carbon footprint. At my own judgment, backed up by comments from my mentors during P4 and skepticism received at VB, I decided not to use a concrete floor to support growing systems, but rather concrete beams under only the rails of the growing systems. From years of experience of working in greenhouses, I know people in greenhouses just work on tamped soil, so no other type of floor is needed to compensate for the concrete floor either. In tomato greenhouses there are rail tracks on the ground over which carts can drive, but they are not applicable in hybrid urban vertical farms, nor in my intepretation (lettuce greenhouse) of the case study. The reconsideration of concrete floors greatly reduced the carbon footprint of the modules (50-85%), as discussed in p6 carbon c2 system.

Second, material changes were applied in the design of the growing systems. Aluminum 5 mm thick in the container belly, fronts, and the NFT system sheets has been replaced with slightly thinner polycarbonate. This not only has a 15 times lower production factor, but is even more recyclable, and is called lower density. This has greatly reduced the carbon footprint of the systems, even while adding concrete beams to support the growing systems' rails to the growing systems' carbon footprint calculations.

personal reflection

I will reflect upon the personal experiences during the graduation period by means of three remarks:

1. *The development of the purpose of research.*

Two key factors changed the direction of this thesis. First, my growing awareness about a food shortage by 2050 led me to consider reusing greenhouse components for urban vertical farming rather than just any building design. This prompted an exploration of how greenhouse components could be reused in growing systems. Second, the skepticism expressed by my colleagues at VB; despite their enthusiasm about reusing greenhouse components, they were adamant that you cannot simply apply those components in new structures. They also indicated that it is already completely impossible to merge a collection of components from different greenhouses into a design because they simply weren't designed to fit together. Therefore, the decision was made to focus on designing a modular system that maximizes the reuse of components. With these considerations in mind, the idea emerged to design an optimized urban vertical farm that made efficient use of materials and space. Also, utilizing natural daylight became a primary focus, as it was understood that any space optimization would be meaningless without a strong foundation in daylight utilization. While personally regretting that the modules are essentially repurposed greenhouse sections rather than innovative designs, the constraints imposed by greenhouse construction principles and the need for high yield per m^2 made designing modules in other formats illogical. However, the advantage lies in the increased circularity achieved through the reuse of reclaimed materials during demolition.

With the method of reuse, modular rebuilding, and optimization in this thesis, the design might not be architecturally appealing. However, it is a viable and buildable concept that can provide food in an efficient and energy efficient manner in the years to 2050 and beyond. The fact that my supervisor at VB sees potential in the design gives me great confidence that I made the right choice with the change of direction in this thesis and created a more relevant and useful design than I would have done initially.

2. *An iterative research and design process.*

In my bachelors I always strived to change my linear design process to a more iterative one because that was one of my weaknesses. I never really managed to, though. Throughout this thesis, I stepped back more often than I remember in order to make improvements that were beneficial to the overall process. In addition, I changed my research approach after a few weeks. So, I can say that I believe that I have worked more iteratively than ever before, and that I am pleasantly surprised with the results. I recognize that there is still much room for improvement beyond what I have done now, but it is a step forward. They say that one does not graduate to get a degree, but one graduates to learn. And I believe that I have learned; academically and personally.

3. *A pleasant cooperation with practice.*

I started drafting a thesis research question and approaching horticultural companies back in July 2022. This was because I wanted to avoid at all costs that I would be bored with my graduation research after a few months. Now, at the end of the research, I can honestly say that I still find the research interesting.

I had some stress just before P4 to finish the carbon footprint calculations, and some stress again just before P5 to finish the carbon footprint calculations for the improved design. For a short while, this created some aversion to the thesis as a whole. However, it did not diminish my interest in the horticultural sector. Investigating an innovative design using greenhouse construction knowledge, that's what kept my curiosity for months. So I proudly mention that I accepted a research and development position at VB with the proviso that I graduate on June 20, 2023. And if I do, I will continue the development of the sliding and rotating growing ssytem that has been designed in this thesis.

4. My opinion on the result.

I would have liked to have invested more time into the urban integration of hybrid urban vertical farms. In my head it is perfectly clear how the farm can make use of urban facilities, but to get that right on paper and visualize it is difficult. I also spent the period between P4 and P5 mostly making design improvements and shortening my report (which I did quite well, if I do say so myself, I scraped off about 50 pages). Therefore, I did not use that time to work much on urban integration. However, I have some renders ready for the P5 presentation that will give a better picture as it is in my head right now.

I am happy with the end result, although I wish I could do all the follow-up research in the discussion myself. I am mostly proud that I was able to deliver what I believe to be a socially relevant design with potential to be really built, and what I believe is a sustainable alternative for vertical farming. I can only hope that Delft University of Technology realizes this as well, so that the more academically oriented university and the rough horticultural sector are able to genuinely achieve a balance, as the approach of this dissertation was originally intended.

To the reader of my thesis,
Thank you,

Koen Verbraeken

back matter

bibliography

Aerofarms. (2023). *Cutting-Edge Vertical Farming Technology Platform*. Retrieved February 01, 2023, from https://www.aerofarms.com/how-we-grow/

Aerofarms. (2023). Racking vertical farming typology [Photograph]. https://www.aerofarms.com/

Agritecture. (2019). Hanging vertical farming typology [Photograph]. https://www.agritecture.com/blog/2019/6/24/plenty-unveils-its-largest-most-efficient-farm-yet

Agritecture. (2019). *Plenty unveils its largest, most efficient farm yet*. Retrieved February 02, 2023, from https://www.agritecture.com/blog/2019/6/24/plenty-unveils-its-largest-most-efficient-farm-yet

Agrotonomy. (2022). *Tower Farms FAQs*. Retrieved February 02, 2023, from https://agrotonomy.com/commercial/

Agrotonomy. (2022). Towering vertical farming typology [Photograph]. https://agrotonomy.com/commercial/

Alexandratos, N. and J. Bruinsma. 2012. *World agriculture towards 2030/2050: the 2012 revision*. ESA Working paper No. 12-03. Rome, FAO.

ArcelorMittal. (n.d.). *Magnelis*. Retrieved May 10, 2023, from https://belgium.arcelormittal.com/innovatie/productinnovatie/magnelis/

Astee, L. Y., & Kishnani, N. T. (2010). Building integrated agriculture: Utilising rooftops for sustainable food crop cultivation in Singapore. *Journal of Green Building, 5*(2), 105–113. https://doi.org/10.3992/jgb.5.2.105

Avisomo. (2022). *Products*. Retrieved February 09, 2023, from https://avisomo.com/products/

Avisomo. (2022). Riding vertical farming typology [Photograph]. https://vertical-farming.net/blog/2023/01/19/avisomo-nominated-for-fruit-logistica-innovation-award-2023/

Barbosa, G., Gadelha, F., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., Wohlleb, G., & Halden, R. (2015). Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. Conventional agricultural methods. *International Journal of Environmental Research and Public Health, 12*(6), 6879–6891. https://doi.org/10.3390/ijerph120606879

Benke, K., & Tomkins, B. (2017). Future food-production systems: vertical farming and controlled-environment agriculture. *Sustainability: Science Practice and Policy, 13*(1), 13–26. https://doi.org/10.1080/15487733.2017.1394054

Berg Hortimotive. (n.d.). *BeMotion AGV Pepper*. Retrieved April 25, 2023, from https://berghortimotive.com/nl/oogst-transport/paprika-agv

Bergsma, G., Broeren, M., & Uijttewaal, M. (2021). *CO2-reductie met circulaire kunststoffen in Nederland Scenario-analyse voor 2030 en diverse praktijkcases*. Retrieved June 11, 2023, from https://www.rethinkplastics.nl/wp-content/uploads/2021/11/CE_Delft_210236_CO2-reductie_met_circulaire_kunststoffen_in_Nederland_Def.pdf

Birkby, J. (2016). Vertical Farming. *National Sustainable Agriculture Information Service (ATTRA)*. (available at: https://attra.ncat.org/publication/vertical-farming/)

Boyle, T. (2017). Photoperiod Control Systems for Greenhouse Crops. *Floral Notes, May-June, 4*(6): 2-4.

Bren d'Amour, C., Reitsma, F., Baiocchi, G., Barthel, S., Güneralp, B., Erb, K. H., Haberl, H., Creutzig, F., & Seto, K. C. (2017). Future urban land expansion and implications for global croplands. *Proceedings of the National Academy of Sciences of the United States of America, 114*(34), 8939–8944. https://doi.org/10.1073/pnas.1606036114

Brown, M. E., Antle, J. M., Backlund, P., Carr, E. R., Easterling, W. E., Walsh, M. K., Ammann, C., Attavanich, W., Barrett, C. B., Bellemare, M. F., Dancheck, V., Funk, C., Grace, K., Ingram, J. S. I., Jiang, H., Maletta, H., Mata, T., Murray, A., Ngugi, M., Tebaldi, C. (2015). *Climate change, global food security, and the U.S. food system*. U.S. Global Change Research Program.

Centraal Bureau voor de Statistiek. (2023). *Landbouw; gewassen, dieren en grondgebruik naar bedrijfstype, nationaal* [Dataset]. Retrieved from https://opendata.cbs.nl/statline/#/CBS/nl/dataset/80782ned/table?ts=1642524024433

Consumentenbond. (2022). *Stroomprijs per kWh*. Retrieved February 02, 2023, from https://www.consumentenbond.nl/energie-vergelijken/kwh-prijs

Cooper, A. (2017). *Going up? Vertical farming in high-rises raises hopes*. Pacific Standard. Retrieved January 03, 2023, from https://psmag.com/environment/farming-in-high-rises-raises-hopes-3705

Cordis Europa. (2020). *Sustainable growing media for vegetable cultivation*. Retrieved April 17, 2023, from https://cordis.europa.eu/article/id/418477-greenhouse-crops

Despommier, D. (2010). *The vertical farm: feeding the world in the 21st century*. New York, Thomas Dunne Books/St. Martin's Press.

Diver S. (2006). Aquaponics-Integration of Hydroponics with Aquaculture. *National Sustainable Agriculture Information Service (ATTRA)*. (available at: https://attra.ncat.org/product/aquaponics-integration-of-hydroponics-with-aquaculture/)

Dlubal. (n.d.). *Cross-section properties*. Retrieved November 15, 2022, from https://www.dlubal.com/en/cross-section-properties/

Drents Overijsselse Delta. (n.d.). Wastewater treatment plant, a renewable water source [Photograph]. https://www.wdodelta.nl/rondleiding-rwzi

Dutch Greenhouses. (n.d.-b). *Aluminium System*. Retrieved December 05, 2022, from https://www.dutchgreenhouses.com/en/technology/aluminium-system/

Dutch Greenhouses. (n.d.-g). *CO_2 enrichment*. Retrieved December 05, 2022, from https://www.dutchgreenhouses.com/en/technology/co2-enrichment/

Dutch Greenhouses. (n.d.-d). *Combined Heat & Power - CHP*. Retrieved December 05, 2022, from https://www.dutchgreenhouses.com/en/technology/combined-heat-power/

Dutch Greenhouses. (n.d.-e). *Greenhouse Cooling*. Retrieved December 05, 2022, from https://www.dutchgreenhouses.com/en/technology/greenhouse-cooling/

Dutch Greenhouses. (n.d.-l). *Greenhouse Foundation*. Retrieved December 05, 2022, from https://www.dutchgreenhouses.com/en/technology/greenhouse-foundation/

Dutch Greenhouses. (n.d.-c). *Greenhouse Glass*. Retrieved December 05, 2022, from https://www.dutchgreenhouses.com/en/technology/greenhouse-glass/

Dutch Greenhouses. (n.d.-f). *Greenhouse Heating*. Retrieved December 05, 2022, from https://www.dutchgreenhouses.com/en/technology/heating/

Dutch Greenhouses. (n.d.-j). *Horizontal Screening System*. Retrieved December 05, 2022, from https://www.dutchgreenhouses.com/en/technology/horizontal-screening/

Dutch Greenhouses. (n.d.-m). *Insect Netting*. Retrieved December 05, 2022, from https://www.dutchgreenhouses.com/en/technology/insect-netting/

Dutch Greenhouses. (n.d.-i). *Lighting*. Retrieved December 05, 2022, from https://www.dutchgreenhouses.com/en/technology/lighting/

Dutch Greenhouses. (n.d.-n). *Service Building*. Retrieved December 05, 2022, from https://www.dutchgreenhouses.com/en/technology/service-building/

Dutch Greenhouses. (n.d.-a). *Venlo Greenhouse Structure*. Retrieved December 05, 2022, from https://www.dutchgreenhouses.com/en/technology/venlo-greenhouse-structure/

Dutch Greenhouses. (n.d.-h). *Ventilation Mechanism*. Retrieved December 05, 2022, from https://www.dutchgreenhouses.com/en/technology/ventilation-mechanism/

Dutch Greenhouses. (n.d.-k). Vertical Screening. Retrieved December 05, 2022, from https://www.dutchgreenhouses.com/en/technology/vertical-screening/

Ecofys & Fraunhofer-ISI. (2009). *Methodology for the free allocation of emission allowances in the EU ETS post 2012 Sector report for the glass industry*. Retrieved June 11, 2023, from https://climate.ec.europa.eu/system/files/2016-11/bm_study-glass_en.pdf

Eden Green. (2022). *Eden Green Opens First Phase of $47 Million Vertical Farm in North Texas*. Retrieved February 07, 2023, from https://www.edengreen.com/blog-collection/eden-green-opens-first-phase-of-47-million-vertical-farm-in-north-texas

Eurocode Applied. (n.d.). *Eurocode 3 Table of design material properties for structural steel*. Retrieved January 11, 2023, from https://eurocodeapplied.com/design/en1993/steel-design-properties

Fischer, R.A. & Byerlee, Derek & Edmeades, Gregory. (2014). *Crop yields and global food security: will yield increase continue to feed the world? ACIAR Monograph No. 158*. Australian Centre for International Agricultural Research. Canberra.

Food and Agriculture Organization. (2013). *Food wastage footprint: Impacts on natural resources*.

Food and Agriculture Organization. (2014). *Food losses and waste in the context of sustainable food systems. A report by the high-level panel of experts on food security and nutrition*. Food & Agriculture Organization of the United Nations (FAO).

Food and Agriculture Organization. (2014). *The state of food and agriculture*. Moving forward on food loss and waste reduction. Food & Agriculture Organization of the United Nations (FAO).

Food and Agriculture Organisation. (2018). *The future of food and agriculture – Alternative pathways to 2050*. Rome. 180 pp. (available at www.fao.org/3/I8429EN/i8429en.pdf).

Food and Agriculture Organization. (2022). *The state of food security and nutrition in the World 2022 The state of food security and nutrition in the World 2022: Repurposing food and agricultural policies to make healthy diets more affordable*. Food & Agriculture Organization of the United Nations (FAO).

Food Sustainability Index. (2018). *Fixing food 2018: best practices towards the Sustainable Development Goals*. Retrieved December 12, 2022, from http://foodsustainability.eiu.com/whitepaper-2018/

Galvanizeit. (n.d.). *Life-Cycle Assessment*. Retrieved June 11, 2023, from https://galvanizeit.org/hot-dip-galvanized-steel-for-parking-structures/environmental-advantages/life-cycle-assessment

Galvanizeit. (n.d.). *Sustainable Solutions for corrosion protection*. Retrieved May 10, 2023, from https://galvanizeit.org/uploads/publications/Sustainable_Solutions_for_Corrosion_Protection.pdf

Gbiorczyk, K., Sonneveld, P. J., Bot, G. P. A., & von Elsner, B. (2004). The effect of roof inclination on the condensation behaviour of plastic films used as greenhouse covering materials. *Acta Horticulturae, 633*, 127–136. https://doi.org/10.17660/actahortic.2004.633.15

Glastuinbouw Waterpoof. (2019). *Ion Specifiek Telen: Optimalisatie bemesting met ion specifieke sensoren*. Retrieved May 11, 2023, from https://www.glastuinbouwwaterproof.nl/onderzoeken/w19004-ion-specifiek-telen-optimalisatie-bemesting-met-ion-specifieke-sensoren/#_

Gorton, H. (2010). Biological Action Spectra. *Photobiological Sciences Online*. American Society for Photobiology.

Graamans, L., Baeza, E., van den Dobbelsteen, A., Tsafaras, I., & Stanghellini, C. (2018). *Plant factories versus greenhouses: Comparison of resource use efficiency. Agricultural Systems, 160*, 31–43. https://doi.org/10.1016/j.agsy.2017.11.003

Groentennieuws. (n.d.). De Agrobusinessclub vond plaats in het nieuwe pand van VB [Photograph]. https://www.groentennieuws.nl/photos/album/9837/agro-businessclub-westland-bij-vb/#&gid=1&pid=292390

Hemming, S., Waaijenberg, D., Bot, G., Sonneveld, P., de Zwart, F., Dueck, T. A., van Dijk, C. J., Dieleman, J. A., Marissen, N., van Rijssel, E., & Houter, G. (2004). *Optimaal gebruik van natuurlijk licht in de glastuinbouw*. (Rapport / Agrotechnology & Food Innovations; No. nr. 100). Agrotechnology & Food Innovations. https://edepot.wur.nl/40067

Iersel, M. van. (2017). *Re: Can I convert PAR (photo active radiation) value of micro mole/M2/S to Solar radiation in Watt/m2?* Retrieved April 20, 2023, from: https://www.researchgate.net/post/Can-I-convert-PAR-photo-active-radiation-value-of-micro-mole-M2-S-to-Solar-radiation-in-Watt-m2/59ca6422217e201e2b23415f/citation/download.

International Aluminium. (2021). *Greenhouse Gas Emissions Intensity- Primary Aluminium*. Retrieved June 11, 2023, from https://international-aluminium.org/statistics/greenhouse-gas-emissions-intensity-primary-aluminium/

International Peatland Society. (2021). *IPC 2021 16th International Peatland Congress*. Retrieved June 11, 2023, from https://ipc2021.publicon.ee/userfiles/ipc2021/IPC%202021%20proceedings_oral%20presentations_f.pdf

Jensen, M. H. (2002). Controlled environment agriculture in deserts, tropics and temperate regions - a world review. *Acta Horticulturae, 578*, 19–25. https://doi.org/10.17660/actahortic.2002.578.1

Koppert Cress. (2021). One-layer growing system [Photograph]. https://www.koppertcress.com/nl/travel-stories/innovatieve-kas

Koppert Cress. (2021a). *Start-up BBBLS bouwt CO2 neutrale kas bij Koppert Kress*. Retrieved January 12, 2023, from https://www.koppertcress.com/nl/nieuws/start-up-bbbls-bouwt-co2-neutrale-kas-bij-koppert-cress

Koppert Cress. (2021b). *First PAR+ coating applied*. Retrieved January 12, 2023, from https://www.koppertcress.com/en/nieuws/first-par-coating-applied

Kwekenmetled.nl (n.d.). *Lichtspectrum LED kweeklampen*. Retrieved December 06, 2022, from https://kwekenmetled.nl/lichtspectrum-led-kweeklampen

Mahasenan, N., Smith, S., & Humphreys, K. (2003). The cement industry and global climate ChangeCurrent and potential future cement industry CO2 emissions. In *Greenhouse Gas Control Technologies - 6th International Conference* (pp. 995–1000). Elsevier.

Mir M. S., Naikoo N. B., Kanth R. H., Bahar F. A., Bhat M. A., Nazir A., Mahdi S. S., Amin Z., Singh L., Raja W., Saad A. A., Bhat T. A., Palmo T., Ahngar T. A. (2022). *Vertical farming: The future of Agriculture: A review. The Pharma Innovation Journal. 2022; 11*(2): 1175-1195.

Mohammadkhani V. & Sonneveld P.J. (2003). *Haalbaarheidsstudie energiebesparend bodemafdekfolie*. Agrotechnology & Food Innovations.

Montel. (2023). *AG Tech vertical cultivation*. Retrieved February 10, 2023, from https://www.montel.com/en/applications/ag-tech-vertical-cultivation

Montel. (2023). Sliding vertical farming typology [Photograph]. https://www.montel.com/en/applications/ag-tech-vertical-cultivation

Montgomery D. R. (2007). *Soil erosion and agricultural sustainability. Proceedings of the National Academy of Sciences of the United States of America, 104*(33), 13268–13272. https://doi.org/10.1073/pnas.0611508104.

My Agriculture Information Bank. (2018). E*ssential plant nutrients for horticultural systems*. Retrieved December 06, 2022, from https://agriinfo.in/essential-plant-nutrients-for-horticultural-crops-1033/

Navarro, L. M., & Pereira, H. M. (2012). Rewilding abandoned landscapes in Europe. *Ecosystems (New York, N.Y.), 15*(6), 900–912. https://doi.org/10.1007/s10021-012-9558-7

Nedal. (n.d.). *Alloy Data Sheet EN-AW 6063 [AlMg0.7Si] (Type: General extrusion alloy)*. Retrieved December 21, 2022, from https://www.nedal.com/wp-content/uploads/2017/11/Nedal-alloy-Datasheet-EN-AW-6063.pdf

OCAP. (n.d.). *Ocap^{TM} Optimaal*. Retrieved May 11, 2023, from https://ocapoptimaal.nl/

Onder Glas. (2016). *Westland kampt met verouderd kassenbestand*. Retrieved May 10, 2023, from https://www.onderglas.nl/westland-kampt-met-verouderd-kassenbestand/

Onder Glas. (2020). *Gereinigd afvalwater waardevolle gronstof voor de tuinbouw*. Retrieved May 11, 2023, from https://www.onderglas.nl/gereinigd-afvalwater-waardevolle-grondstof-voor-de-tuinbouw/

PBL Netherlands Environmental Assessment Agency. (2021). *Decarbonisation Options for the Dtuch Polycarbonate Industry*. Retrieved June 11, 2023, from https://www.pbl.nl/sites/default/files/downloads/pbl-2021-decarbonisation-options-for-the-dutch-polycarbonate-industry-4580.pdf

Pelikaan. (n.d.). *Qlipr*. Retrieved May 11, 2023, from https://www.pellikaanq.com/products/qlipr

Philips. (2022). Philips GreenPower LED production module [Photograph]. https://www.signify.com/en-us/blog/archive/led/philips-greenpower-led-toplighting-compact

Philips. (2022). *Philips GreenPower LED production module*. Retrieved April 21, 2023, from https://www.lighting.philips.nl/producten/horticulture/products/greenpower-led-production-module

Primo. (2020). *CO2-emission calculation at Primo*. Retrieved June 11, 2023, from https://www.primo.com/system/blog/post/co2-emission-calculation-at-primo?PID=25155&M=NewsV2&Action=1

Principato, L., Mattia, G., Di Leo, A., & Pratesi, C. A. (2021). The household wasteful behaviour framework: A systematic review of consumer food waste. *Industrial Marketing Management, 93*, 641–649. https://doi.org/10.1016/j.indmarman.2020.07.010

Produce Grower. (2017). *Pollination basics for controlled environments*. Retrieved December 06, 2022, from https://www.producegrower.com/article/pollination-basics-for-controlled-environments/

Reece, J. B., Urry, L. A., Cain, M. L., Wasserman, S. A., Minorsky, P. V., & Jackson, R. B. (2011). *Campbell Biology: Global Edition* (9th ed.). Pearson Education.

Renold. (n.d.). *Renold SD Roller Chain Standard Duty Chain*. Retrieved April 19, 2023, from https://www.renold.com/products/industrial-transmission-chain/general-transmission-chain/renold-sd/

Ridder. (n.d.). *Ridder NoNa+*. Retrieved May 10, 2023, from https://ridder.com/nl/ridder-nona/

Royal Brinkman. (n.d.). *Hoe kun je substraatmatten recyclen en hergebruiken*. Retrieved May 10, 20203, from https://royalbrinkman.nl/kennisbank-teeltwisseling/substraatmatten-recyclen-hergebruiken

Schettini, E., & Vox, G. (2010). Greenhouse plastic films capable of modifying the spectral distribution of solar radiation. *Journal of Agricultural Engineering, 41*(1), 19. https://doi.org/10.4081/jae.2010.1.19

Shen, P., Zhang, B., Li, Z., Pang, X., & Deng, W. (2022). Forming mechanism, mechanical properties, and corrosion properties of aluminum alloy sheet with gradient structure processed by plastic flow machining. *Journal of Alloys and Compounds, 933*(167800), 167800. https://doi.org/10.1016/j.jallcom.2022.167800

Sky Greens. (2014). Rotating vertical farming typology [Photograph]. https://www.thepeakmagazine.com.sg/gourmet-travel/nespresso-sky-greens/

Sky Greens. (2014). *Sky Greens Vertical Farming System – The world's first low carbon hydraulic commercial farming system*. Retrieved February 13, 2023, from https://www.skygreens.com/technology/

Smith, A., Watkiss, P., Tweddle, G., & McKinnon, A. C. (2005). *The Validity of Food Miles as an Indicator of Sustainable Development: Final Report for DEFRA*. AEA Technology.

Soffer, H., Burger, D. W., & Lieth, J. H. (1991). Plant growth and development of Chrysanthemum and Ficus in aero-hydroponics: response to low dissolved oxygen concentrations. *Scientia Horticulturae, 45*(3–4), 287–294. https://doi.org/10.1016/0304-4238(91)90074-9

Soszna, C. (2020). *Historie Westlandse Kassenbouw*. www.drukcase.nl

United Nations Department of Economic and Social Affairs, Population Division (2019). *World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420)*. New York: United Nations.

United Nations Department of Economic and Social Affairs, Population Division (2022a). *World Population Prospects 2022: Summary of Results*. UN DESA/POP/2022/TR/NO. 3.

United Nations Department of Economic and Social Affairs. (2022b). *The sustainable development goals report 2022*. United Nations.

University of Massachusetts Amherst. (n.d.). *Water Quality for Crop Production*. Retrieved December 06, 2022, from https://ag.umass.edu/greenhouse-floriculture/greenhouse-best-management-practices-bmp-manual/water-quality-for-crop

United States Department of Agriculture. 2022. *Farms and Land in Farms 2021 Summary. February 2022*. (available at https://downloads.usda.library.cornell.edu/usda-esmis/files/5712m6524/6h441w232/vx022h58v/fnlo0222.pdf)

United States Environmental Protection Agency. (2022). *Human Health Issues Related to Pesticides*. Retrieved December 12, 2022, from https://www.epa.gov/pesticide-science-and-assessing-pesticide-risks/human-health-issues-related-pesticides

VB. (2019). MightVine phase 3 during construction [Photograph]. *Internal VB document retrieved from the MightyVine phase 3 project documentation folder from the VB server.*

Verbraeken, K. (2022). Concrete foundation and recyclable w reinforces plastic foundations [Photograph].

Verbraeken, K. (2023). Turnbuckle [Photograph].

Verbraeken, K. (2023). Two-layer growing system [Photograph].

Verlodt I., Daponte T. & Verschaeren P. (1995). Interference pigments for greenhouse films. *Plasticulture (108)*, 13-26.

von Elsner, B., Briassoulis, D., Waaijenberg, D., Mistriotis, A., von Zabeltitz, C., Gratraud, J., Russo, G., & Suay-Cortes, R. (2000). Review of structural and functional characteristics of greenhouses in European union countries: Part I, design requirements. *Journal of Agricultural Engineering Research, 75*(1), 1–16. https://doi.org/10.1006/jaer.1999.0502

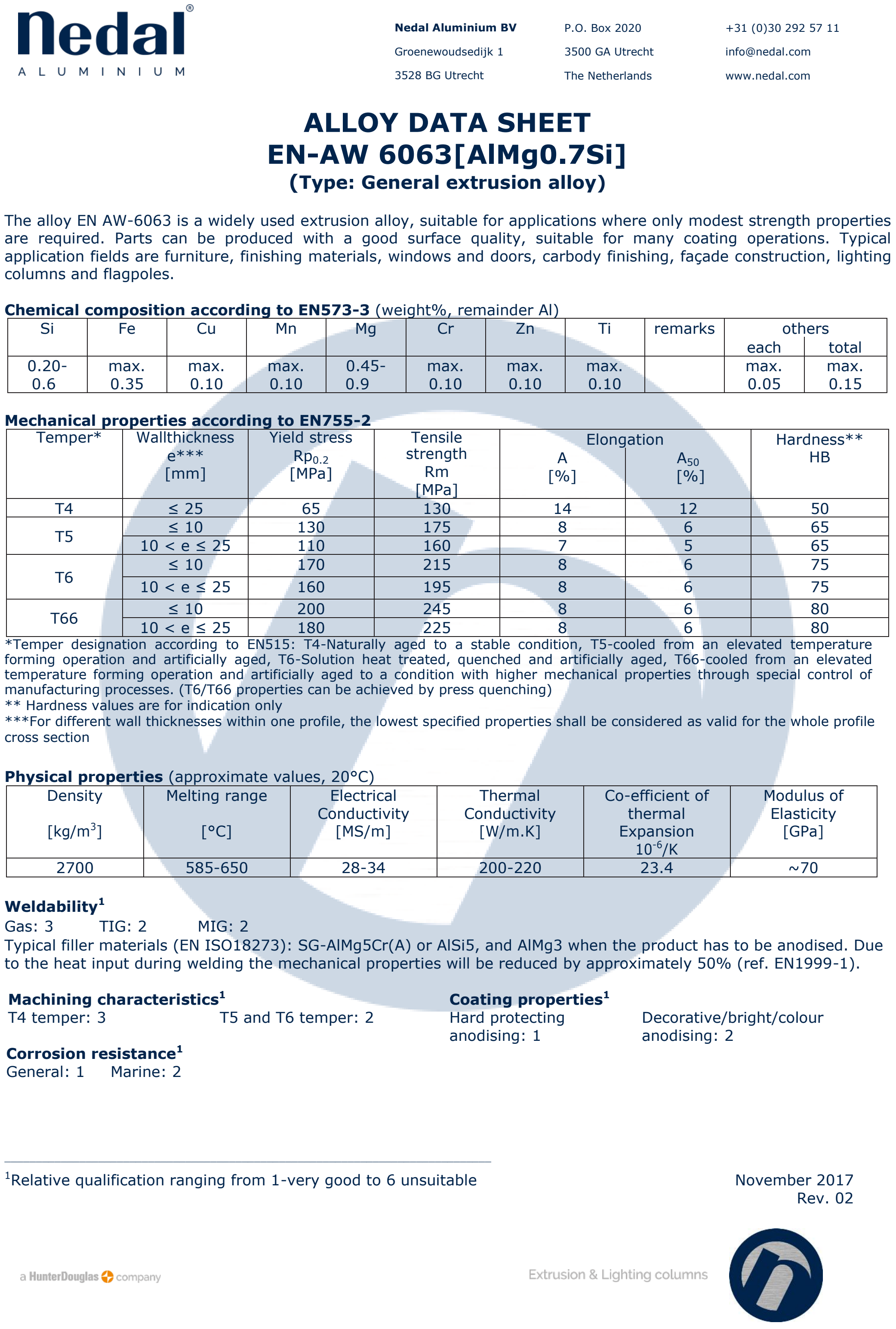
Voshol Warmte-Elektrotechniek. (n.d.). *Hybride belichting*. Retrieved December 21, 2022, https://www.janvoshol.nl/diensten/hybride-belichting/

World Steel Association. (2021). *Our performance: Sustainability Indicators*. Retrieved June 11, 2023, from https://worldsteel.org/steel-topics/sustainability/sustainability-indicators/

Yuan, G. N., Marquez, G. P. B., Deng, H., Iu, A., Fabella, M., Salonga, R. B., Ashardiono, F., & Cartagena, J. A. (2022). A review on urban agriculture: technology, socio-economy, and policy. *Heliyon, 8*(11), e11583. https://doi.org/10.1016/j.heliyon.2022.e11583

appendix 1

Alloy data sheet from aluminium supplier Nedal Aluminium regarding the alloy EN AW-6063 T66.



Nedal® ALUMINIUM

Nedal Aluminium BV
Groenewoudsedijk 1
3528 BG Utrecht

P.O. Box 2020
3500 GA Utrecht
The Netherlands

+31 (0)30 292 57 11
info@nedal.com
www.nedal.com

ALLOY DATA SHEET
EN-AW 6063[AlMg0.7Si]
(Type: General extrusion alloy)

The alloy EN AW-6063 is a widely used extrusion alloy, suitable for applications where only modest strength properties are required. Parts can be produced with a good surface quality, suitable for many coating operations. Typical application fields are furniture, finishing materials, windows and doors, carbody finishing, façade construction, lighting columns and flagpoles.

Chemical composition according to EN573-3 (weight%, remainder Al)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	remarks	others	
									each	total
0.20-0.6	max. 0.35	max. 0.10	max. 0.10	0.45-0.9	max. 0.10	max. 0.10	max. 0.10		max. 0.05	max. 0.15

Mechanical properties according to EN755-2

Temper*	Wallthickness e*** [mm]	Yield stress $Rp_{0.2}$ [MPa]	Tensile strength Rm [MPa]	Elongation		Hardness** HB
				A [%]	A_{50} [%]	
T4	≤ 25	65	130	14	12	50
T5	≤ 10	130	175	8	6	65
	10 < e ≤ 25	110	160	7	5	65
T6	≤ 10	170	215	8	6	75
	10 < e ≤ 25	160	195	8	6	75
T66	≤ 10	200	245	8	6	80
	10 < e ≤ 25	180	225	8	6	80

*Temper designation according to EN515: T4-Naturally aged to a stable condition, T5-cooled from an elevated temperature forming operation and artificially aged, T6-Solution heat treated, quenched and artificially aged, T66-cooled from an elevated temperature forming operation and artificially aged to a condition with higher mechanical properties through special control of manufacturing processes. (T6/T66 properties can be achieved by press quenching)
** Hardness values are for indication only
***For different wall thicknesses within one profile, the lowest specified properties shall be considered as valid for the whole profile cross section

Physical properties (approximate values, 20°C)

Density [kg/m^3]	Melting range [°C]	Electrical Conductivity [MS/m]	Thermal Conductivity [W/m.K]	Co-efficient of thermal Expansion 10^{-6}/K	Modulus of Elasticity [GPa]
2700	585-650	28-34	200-220	23.4	~70

Weldability[1]
Gas: 3 TIG: 2 MIG: 2
Typical filler materials (EN ISO18273): SG-AlMg5Cr(A) or AlSi5, and AlMg3 when the product has to be anodised. Due to the heat input during welding the mechanical properties will be reduced by approximately 50% (ref. EN1999-1).

Machining characteristics[1]
T4 temper: 3 T5 and T6 temper: 2

Coating properties[1]
Hard protecting anodising: 1 Decorative/bright/colour anodising: 2

Corrosion resistance[1]
General: 1 Marine: 2

---

[1] Relative qualification ranging from 1-very good to 6 unsuitable

November 2017
Rev. 02

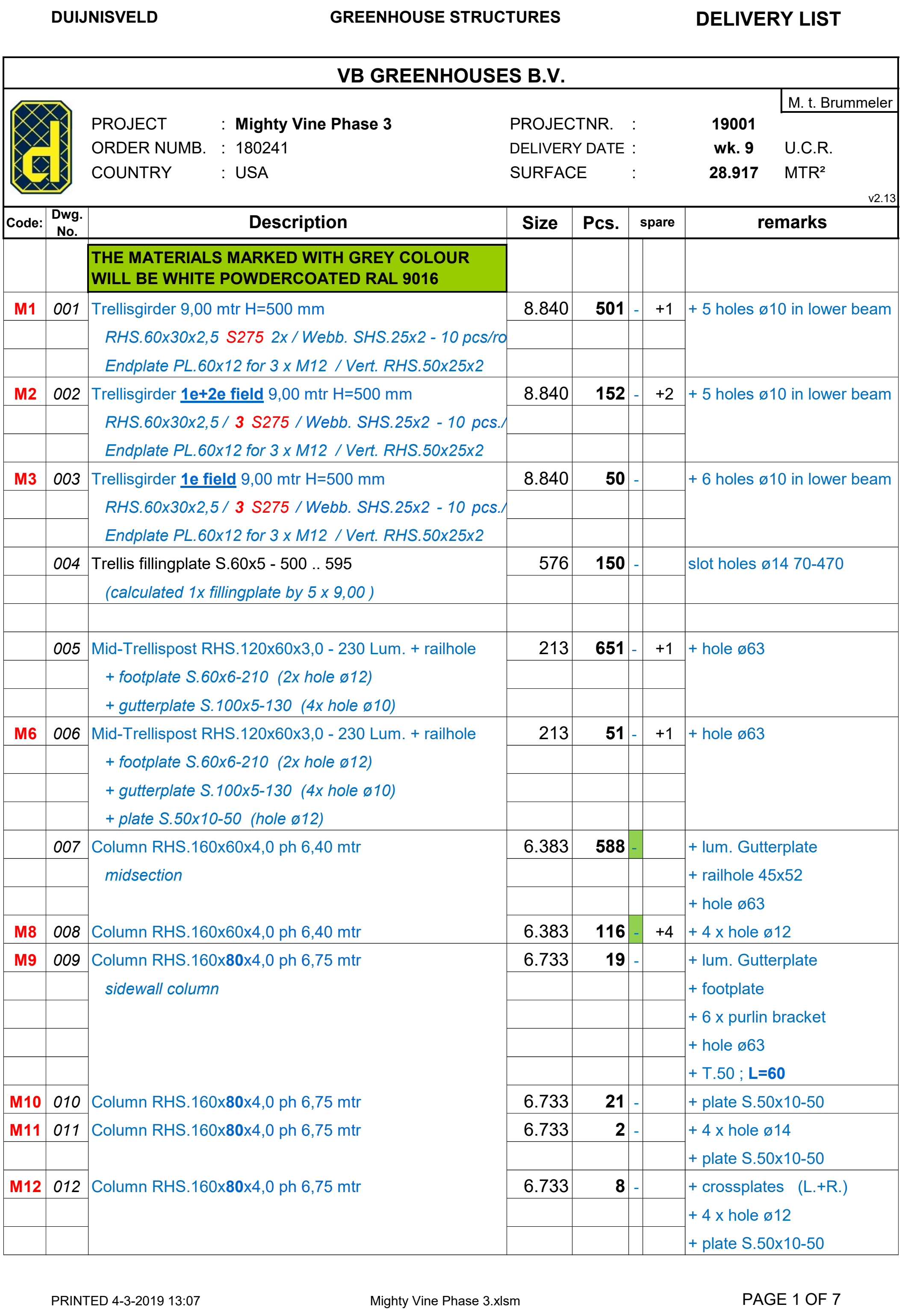
a HunterDouglas company

Extrusion & Lighting columns

appendix 2

appendix 2a

Order list for steel components from steel supplier Duijnisveld Greenhouse Structures.



DUIJNISVELD **GREENHOUSE STRUCTURES** **DELIVERY LIST**

VB GREENHOUSES B.V.

M. t. Brummeler

PROJECT	: **Mighty Vine Phase 3**	PROJECTNR. :	**19001**	
ORDER NUMB.	: 180241	DELIVERY DATE :	**wk. 9**	U.C.R.
COUNTRY	: USA	SURFACE :	**28.917**	MTR²

v2.13

Code:	Dwg. No.	Description	Size	Pcs.	spare		remarks
		THE MATERIALS MARKED WITH GREY COLOUR WILL BE WHITE POWDERCOATED RAL 9016					
M1	*001*	Trellisgirder 9,00 mtr H=500 mm	8.840	**501**	-	+1	+ 5 holes ø10 in lower beam
		RHS.60x30x2,5 S275 2x / Webb. SHS.25x2 - 10 pcs/ro					
		Endplate PL.60x12 for 3 x M12 / Vert. RHS.50x25x2					
M2	*002*	Trellisgirder **1e+2e field** 9,00 mtr H=500 mm	8.840	**152**	-	+2	+ 5 holes ø10 in lower beam
		*RHS.60x30x2,5 / **3** S275 / Webb. SHS.25x2 - 10 pcs./*					
		Endplate PL.60x12 for 3 x M12 / Vert. RHS.50x25x2					
M3	*003*	Trellisgirder **1e field** 9,00 mtr H=500 mm	8.840	**50**	-		+ 6 holes ø10 in lower beam
		*RHS.60x30x2,5 / **3** S275 / Webb. SHS.25x2 - 10 pcs./*					
		Endplate PL.60x12 for 3 x M12 / Vert. RHS.50x25x2					
	004	Trellis fillingplate S.60x5 - 500 .. 595	576	**150**	-		slot holes ø14 70-470
		(calculated 1x fillingplate by 5 x 9,00)					
	005	Mid-Trellispost RHS.120x60x3,0 - 230 Lum. + railhole	213	**651**	-	+1	+ hole ø63
		+ footplate S.60x6-210 (2x hole ø12)					
		+ gutterplate S.100x5-130 (4x hole ø10)					
M6	*006*	Mid-Trellispost RHS.120x60x3,0 - 230 Lum. + railhole	213	**51**	-	+1	+ hole ø63
		+ footplate S.60x6-210 (2x hole ø12)					
		+ gutterplate S.100x5-130 (4x hole ø10)					
		+ plate S.50x10-50 (hole ø12)					
	007	Column RHS.160x60x4,0 ph 6,40 mtr	6.383	**588**	-		+ lum. Gutterplate
		midsection					+ railhole 45x52
							+ hole ø63
M8	*008*	Column RHS.160x60x4,0 ph 6,40 mtr	6.383	**116**	-	+4	+ 4 x hole ø12
M9	*009*	Column RHS.160x**80**x4,0 ph 6,75 mtr	6.733	**19**	-		+ lum. Gutterplate
		sidewall column					+ footplate
							+ 6 x purlin bracket
							+ hole ø63
							+ T.50 ; **L=60**
M10	*010*	Column RHS.160x**80**x4,0 ph 6,75 mtr	6.733	**21**	-		+ plate S.50x10-50
M11	*011*	Column RHS.160x**80**x4,0 ph 6,75 mtr	6.733	**2**	-		+ 4 x hole ø14
							+ plate S.50x10-50
M12	*012*	Column RHS.160x**80**x4,0 ph 6,75 mtr	6.733	**8**	-		+ crossplates (L.+R.)
							+ 4 x hole ø12
							+ plate S.50x10-50

PRINTED 4-3-2019 13:07 Mighty Vine Phase 3.xlsm PAGE 1 OF 7

VB GREENHOUSES B.V.

M. t. Brummeler

PROJECT : **Mighty Vine Phase 3** PROJECTNR. : **19001**
ORDER NUMB. : 180241 DELIVERY DATE : **wk. 9** U.C.R.
COUNTRY : USA SURFACE : **28.917** MTR²

v2.13

Code:	Dwg. No.	Description	Size	Pcs.	spare		remarks
M13	*013*	Column RHS.160x**80**x4,0 ph 6,75 mtr	6.733	**47**	-	+1	+ lum. Gutterplate
		sidewall (intermediate column)					+ footplate
							+ hole ø63
							+ 3 x hole ø12
							+ plate S.50x10-50
M14	*014*	Column RHS.160x**80**x4,0 ph 6,75 mtr	6.733	**4**	-		+ crossplates (L.+R.)
M15	*015*	Column RHS.160x**80**x4,0 ph 6,75 mtr	2.543	**1**	-		+ lum. Gutterplate
		sidewall (intermediate column) on doorbeam					+ footplate
							+ hole ø63
							+ 2 x hole ø12
							+ plate S.50x10-50
M16	*016*	Doorbeam RHS.160x80x4	4.420	**1**	-		
		+ 8 x hole ø14					
		+ 2x endplate S.160x10-180 (4x hole ø14)					
	017	Crossbrace ø10 - 4950 .. 5600	5.000	**226**	-	+2	
		inside crossbrace					
M18	*018*	Crossbrace ø10 - 3200 .. 3750	3.330	**32**	-		
		sidewall crossbrace					
M19	*019*	Crossbrace ø10 - 6350 .. 7100	6.800	**8**	-		
		endwall crossbrace					
	020	Crossbrace-beam BS.120x60x3,0 section 4,50 mtr.	4.440	**56**	-		steel foundation pole 160x60
							first bolt 285 mm under pile
							pitch **165** mm
	021	Upper-crossbr.beam BS.50x50x2,0 section 4,50 mtr.	4.440	**57**	-	+1	brace ø10
	022	Middle-crossbr.beam BS.50x50x2,0 section 4,50 mtr.	4.440	**57**	-	+1	brace ø10
M23	*023*	Upper-crossbr.beam BS.50x50x2,0	2.170	**8**	-		
M24	*024*	Middele-crossbr.beam BS.50x50x2,0	2.170	**8**	-		
	025	Cross-windbrace ø8 - 4,50 roof/4,50 mtr. Section	6.030	**110**	-	+2	
	026	Sidewall guttersupport BS.50x50x2,0	4.453	**51**	-		
		+ 3 x hole ø12 mm					
		+ plate S.40x8-185 (2x hole ø10)					
	027	Sidewall-guttersupport brace ø10	4.600	**108**	-	+2	
	028	Sidewall guttersupport dilatation RHS.100x50x2,5	4.600	**51**	-		
		+ 2 x hole ø63 mm					
		+ 2 x gutterplate S.100x5-130 (4x hole ø10)					

VB GREENHOUSES B.V.

M. t. Brummeler

PROJECT : **Mighty Vine Phase 3**
ORDER NUMB. : 180241
COUNTRY : USA

PROJECTNR. : **19001**
DELIVERY DATE : **wk. 9** U.C.R.
SURFACE : **28.917** MTR²

v2.13

Code:	Dwg. No.	Description	Size	Pcs.		spare	remarks
	029	Snowpipe support bracket RHS.100x50x3	115	**58**	-		
		+ 2 x hole ø10 mm					
		+ hole ø63 mm					
		SIDE/FRONTWALL PURLIN					**EXPEDITIE :**
		MAGNELIS S250GD+ZM					**Code op gording geprint**
M210	*M210*	Sidewall purlin U.80x40x2,0	4.496	**99**	b	+1	punching pattern ctc 750 mm
M211	*M211*	Sidewall purlin U.80x40x2,0	4.426	**49**	b		punching pattern ctc 750 mm
M212	*M212*	Sidewall-corner-purlin U.80x40x2,0	4.663	**2**	b		punching pattern ctc 375 mm
M213	*M213*	Sidewall-corner-purlin U.80x40x2,0	4.663	**2**	b		punching pattern ctc 375 mm
M214	*M214*	Sidewall-corner-purlin U.80x40x2,0	4.628	**1**	b		punching pattern ctc 375 mm
M215	*M215*	Sidewall-corner-purlin U.80x40x2,0	4.628	**1**	b		punching pattern ctc 375 mm
M202	*M202*	Sidewall-corner-purlin U.80x40x2,0	4.663	**3**	b	+1	punching pattern ctc 450 mm
M203	*M203*	Sidewall-corner-purlin U.80x40x2,0	4.663	**3**	b	+1	punching pattern ctc 450 mm
M204	*M204*	Sidewall-corner-purlin U.80x40x2,0	4.628	**1**	b		punching pattern ctc 450 mm
M205	*M205*	Sidewall-corner-purlin U.80x40x2,0	4.628	**1**	b		punching pattern ctc 450 mm
M300	*M300*	Frontw.purlin U.100x40x3 ***Rejuvenated***	9.150	**72**	b		punching pattern ctc 900 mm
		continuous girder					
M301	*M301*	Start-Frontw.purlin U.100x40x3 ***Rejuvenated***	10.385	**4**	b	+1	punching pattern ctc 900 mm
M302	*M302*	End-Frontw.purlin U.100x40x3	8.070	**3**	b		punching pattern ctc 900 mm
M303	*M303*	End-Frontw.purlin U.100x40x3 ***Rejuvenated***	10.190	**4**	b	+1	punching pattern ctc 900 mm
M304	*M304*	End-Frontw.purlin U.100x40x3	8.265	**3**	b		punching pattern ctc 900 mm
M30	*030*	Frontwall-watercolumn RHS.200x120x5 ph 6,75 mtr	6.733	**23**	-		+ lum Gutterplate,
		drain column; str.A					+ plate S.60x8-100
							+ 2 x purlin/screen bracket
		All Frontwallwatercolumns internally					+ 6 x screening plate
		black coated by van der Horst					+ 4 x purlin bracket
							+ footplate
							+ waterdischarge tube Ø159
							+ drainplate S.120x5-188
							+ wirebowstrip S.70x12-140
							+ bracket T.50x6-90
							+ bracket T.60x7-120

VB GREENHOUSES B.V.

M. t. Brummeler

PROJECT : **Mighty Vine Phase 3**
ORDER NUMB. : 180241
COUNTRY : USA

PROJECTNR. : **19001**
DELIVERY DATE : **wk. 9** U.C.R.
SURFACE : **28.917** MTR²

v2.13

Code:	Dwg. No.	Description	Size	Pcs.		spare	remarks
M31	*031*	Frontwall-watercolumn RHS.200x120x5 ph 6,75 mtr	6.733	**2**	-		+ crossplates
M32	*032*	Frontwall-watercolumn RHS.200x120x5 ph 6,75 mtr	6.733	**2**	-		+ crossplates
M33	*033*	Frontwall-watercolumn RHS.200x120x5 ph 6,75 mtr	6.733	**1**	-		cornerpiece
M34	*034*	Frontwall-watercolumn RHS.200x120x5 ph 6,75 mtr	6.733	**1**	-		cornerpiece
M35	*035*	Frontwall-watercolumn RHS.200x120x5 ph 6,75 mtr	6.733	**22**	-		+ lum Gutterplate,
		drain column roofwash side; str.AZ					+ plate S.60x8-100
							+ roofwasher-bracket
		All Frontwallwatercolumns internally					+ 2 x purlin/screen bracket
		black coated by van der Horst					+ 6 x screening plate
							+ 4 x purlin bracket
							+ footplate
							+ waterdischarge tube Ø159
							+ drainplate S.120x5-188
							+ wirebowstrip S.70x12-140
							+ bracket T.50x6-90
							+ bracket T.60x7-120
M36	*036*	Frontwall-watercolumn RHS.200x120x5 ph 6,75 mtr	6.733	**2**	-		+ crossplates
M37	*037*	Frontwall-watercolumn RHS.200x120x5 ph 6,75 mtr	6.733	**2**	-		+ crossplates
M38	*038*	Frontwall-watercolumn RHS.200x120x5 ph 6,75 mtr	6.733	**1**	-		column on corner
M39	*039*	Frontwall-watercolumn RHS.200x120x5 ph 6,75 mtr	6.733	**1**	-		column on corner
M40	*040*	Frontwall-watercolumn RHS.200x120x5 ph 6,75 mtr	6.733	**1**	-		column near door-portal
		Total amount columns RHS.200x120x5		**58**			
	041	Wirebow ribbed ø14 FeB500 roof 4,50 mtr.	4.510	**56**	-		
	042	Wirebow-pushbar BS.60x60x3 roof 4,50 mtr.	4.480	**8**	-		
		+ 2 x plate S.50x10-150 (hole ø18)					
	043	Heating (corner) column RHS.100x50x3	6.490	**8**	-		Frontwall str. A & AZ
		+ footplate					
		+ 6x purlin bracket					
		+ 1x T.50 ; L=190					
		+ 1x T.50 ; L=215 + plate S.50x5-60					
M44	*044*	Door support beam RHS.100x60x3	4.360	**1**	-		
		+ 4x hole ø12 mm					
M45	*045*	Door column RHS.100x50x2,5	4.204	**1**	-		
		+ footplate S.100x6-100					
		+ 1x purlin bracket					
		+ plate S.100x6-140					

VB GREENHOUSES B.V.

M. t. Brummeler

PROJECT : **Mighty Vine Phase 3**
ORDER NUMB. : 180241
COUNTRY : USA

PROJECTNR. : **19001**
DELIVERY DATE : **wk. 9** U.C.R.
SURFACE : **28.917** MTR²

v2.13

Code:	Dwg. No.	Description	Size	Pcs.		spare	remarks
M46	*046*	Door column RHS.100x50x2,5	4.204	**1**	-		
		+ footplate S.100x6-100					
		+ purlin bracket					
		+ plate S.100x6-140					
M47	*047*	Door support column RHS.80x40x3	2.448	**2**	-		
		+ hole ø14/34 mm					
		+ K.40x40x3-38					
		+ plate S.40x5-110					
M48	*048*	Door support column (Speed door) RHS.120x60x3	7.073	**2**	-		
		+ 2x hole ø14/34 mm					
		+ 3x plate S.60x5-80					
		+ U.60x60x60x4-72 + plate S.60x8-190					
		+ U.60x60x60x4-210 + lum. gutterplate S.100x5-120					
M49	*049*	Door support beam RHS.120x60x3	2.760	**1**	-		
		+ 2x plate S.60x10-210					
M50	*050*	Connection Bracket H.80x80x8	140	**2**	-		
		+ 5x hole ø14 mm					
	VM1	Contraplate S.50x5 - 180 .. 240	215	**114**	v	+2	slotted hole ø14x26 - 165
		Contraplate cross.br.beam					
	VM2	Contraplate S.60x5 - 160	160	**244**	v	+4	holes ø12 c.t.c 100
		Contraplate upper + middle-cross.br.beam					
	VM3	Endsection venting bracket Lum BS.80x80x3-105	105	**58**	v		
		+ holes ø10 mm stitch holes 75+75					
	VM4	Wire-strainer M10 8.8 HDG; 2 x eye + 1 x nut.		**490**	v	+12	working length = ± 230 mm
	VM5	Spray paint RAL 9016, 400 ml. Acryl		**4**	v		
	VM6	Service-under-rail BS.50x30x2,0 - 6,00 mtr.	6.000	**21**	v		
	051	Service-rail bracket IPE 120	345	**29**	-		
		+ U.75x71x75x5-250					
		+ RHS.120x60x3-182					
		+ plate S.80x10-114 (4x hole ø14)					
	052	Service-upper rail RHS.140x60x4 S275 - 9,00 mtr.	8.996	**13**	-		
		+ 4 x hole ø14 mm					
	053	Service-upper rail RHS.140x60x4 S275	9.123	**1**	-		
		+ 2 x hole ø14/34 mm					
		+ 5 x hole ø14 mm					

VB GREENHOUSES B.V.

M. t. Brummeler

PROJECT : **Mighty Vine Phase 3** PROJECTNR. : **19001**
ORDER NUMB. : 180241 DELIVERY DATE : **wk. 9** U.C.R.
COUNTRY : USA SURFACE : **28.917** MTR²

v2.13

Code:	Dwg. No.	Description	Size	Pcs.		spare	remarks
	054	End-piece Service-upper rail RHS.140x60x4	620	**1**	-		
		+ hole ø14 mm					
		+ hole ø14/34 mm					
		+ BS.60x3-220					
	055	Diltation/coupling tube RHS.120x50x3	750	**1**	-		
		+ 2 x hole ø14/34 mm					
		+ 2 x staff ø8-100					
	056	Service under-bracket BS.60x30x2 - ±400 under 15°	428	**61**	-		support c.t.c. 2,0 mtr
D57	*057*	Service-bracket RHS.100x60x3	510	**3**	-		
		+ plate S.80x5-110 (2x ø14)					
		+ plate S.60x5-94					
		+ T-profil T.60x60x7-75 (2x ø12)					
	058	Service-under rail RHS.80x50x3	3.998	**1**	-		
		+ 4 x hole ø12					
		+ 2 x handle round 8					
	059	Service-under rail RHS.80x50x3	2.998	**1**	-		
		+ 4 x hole ø12					
	060	Filling tube K.40x20x3	30	**2**	-		
		+ hole ø12					
		Bolts					
	100	Self-drilling screw hexagonal USA 6,3x19 EG - 200		**200**	v		underrail/underconsole
		(packed by 200)					
	101	Bolt M8x16 8.8 HDGI - 200		**400**	v		coupling purlins
	102	Bolt M8x20 8.8 HDGI - 200		**1.000**	v		purlin/column
	103	Bolt M8x30 8.8 HDGI - 200		**200**	v		cross-windbrace Ø8/wire-strainer M10
	104	Bolt M10x40 8.8 HDGI - 100		**1.000**	b		cross-brace Ø10
	105	Bolt M10x50 8.8 HDGI - 100		**70**	v		cross-brace Ø10/column
	106	Bolt M10x60 8.8 HDGI - 100		**1.500**	b		midtrellispost/trellis
	107	Bolt M10x80 8.8 HDGI - 100		**900**	b		column/foundation pile
	108	Bolt M10x90 8.8 HDGI - 100		**500**	b		cross-beam/column M8

VB GREENHOUSES B.V.

M. t. Brummeler

PROJECT : **Mighty Vine Phase 3**
ORDER NUMB. : 180241
COUNTRY : USA

PROJECTNR. : **19001**
DELIVERY DATE : **wk. 9** U.C.R.
SURFACE : **28.917** MTR²

v2.13

Code:	Dwg. No.	Description	Size	Pcs.	spare		remarks
	109	Bolt M10x120 8.8 HDGI - 50		**50**	v		cross-beam column M12
	110	Bolt M10x150 8.8 HDGI - 50		**5**	v		door-beam/door column
	112	Bolt M10x180 8.8 HDGI - 50		**170**	v		purlin/intermediate column
	113	SB Bolt M12x40 incl. nut 8.8 ISO HDGI - 100		**200**	v		service-rail bracket/column
	114	SB Bolt M12x90 incl. nut 8.8 ISO HDGI - 50		**100**	v		upper-rail/service bracket
	115	SB Bolt M12x100 incl. nut 8.8 ISO HDGI - 50		**250**	v		cross-beam/foundation pile
	116	SB Bolt M12x110 incl. nut 8.8 ISO HDGI - 00		**15**	v		column M15/beam M16/colu
	117	SB Bolt M12x190 incl. nut 8.8 ISO HDGI - 25		**5**	v		column M48/beam M16
	118	SB Bolt M12x210 incl. nut 8.8 ISO HDGI - 25		**2.300**	v		trellis/collumn
	119	SB Bolt M16x50 incl. nut 8.8 ISO HDGI - 50		**100**	v		wirebow/column
	120	SB Bolt M16x60 incl. nut 8.8 ISO HDGI - 50		**20**	v		wirebow-pushbar/column
	121	Nut M8 8.8 HDGI - 200		**1.400**	v		
	122	Nut M10 8.8 HDGI - 100		**4.200**	v		
		By trellisbolt apply under every nut and bolthead (Big) Washer.					
		By slot hole in purlin apply Washer					
	123	Washer M8 din126 HDG - 1000		**1.400**	v		
	124	Washer M10 din126 HDG - 200		**5.200**	v		
	125	Washer M12 din126 HDG - 200		**5.200**	v		
	126	Washer M16 din126 HDG - 200		**400**	v		
	127	Big washer M8(ø28) din440R HDG - 200		**400**	v		crossbrace Ø8/wirestrainer
	128	Big washer M10(ø34) din440R HDG - 200		**3.200**	v		wirerstrainer crossbrace R.1
	129	Big washer M12(ø45) din440R HDG - 100		**400**	v		contraring sidewall trellis

Note :
Loading in 40/45 Ft container, EXPORT packing, packaging timber HT treated and marked in accordance with ISPM 15.

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D

VB GREENHOUSES B.V.

M. t. Brummeler

PROJECT : **Mighty Vine (gordingen)**
ORDER NUMB. :
COUNTRY : USA

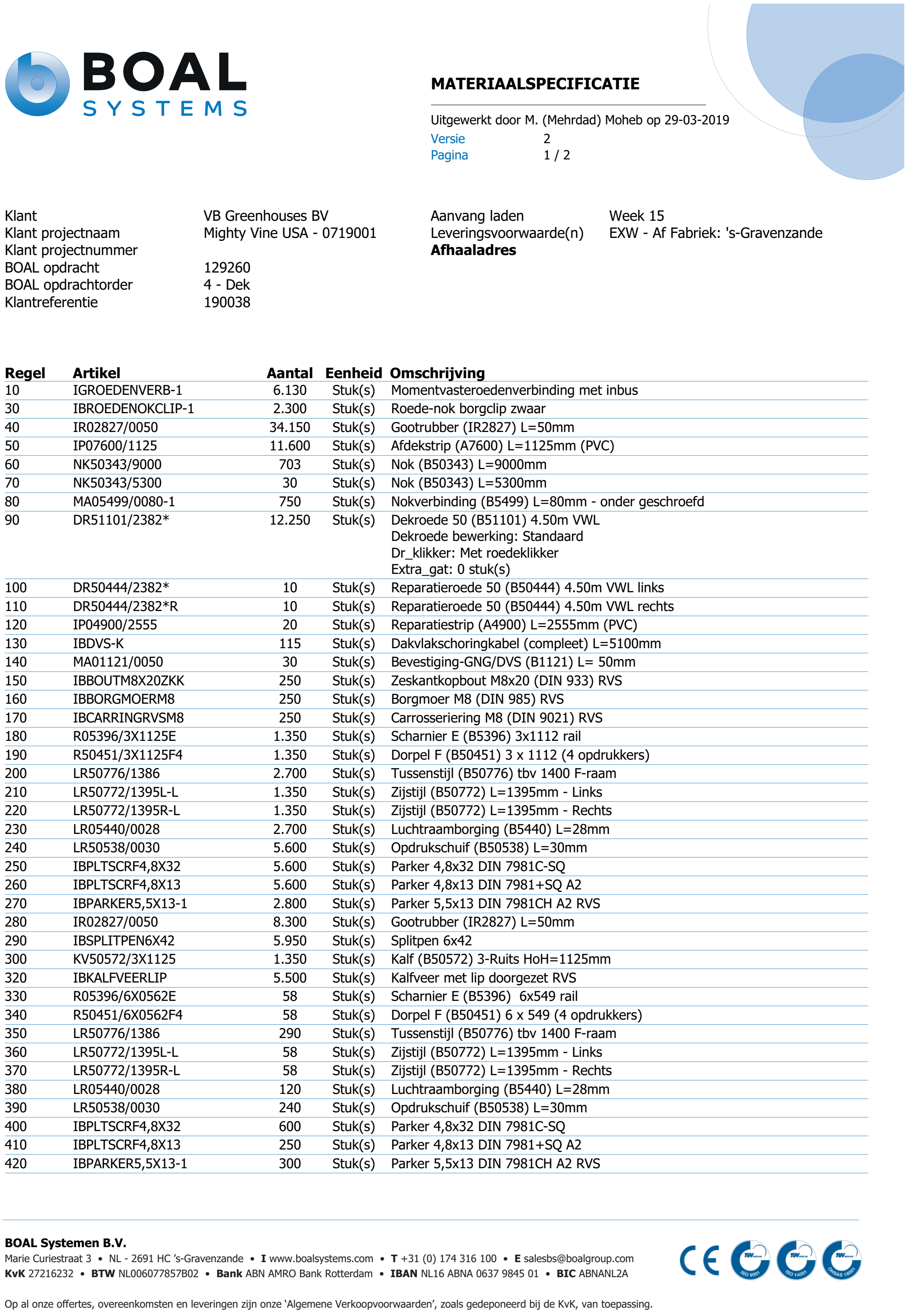
PROJECTNR. : **19098**
DELIVERY DATE : **wk.11** U.C.R.
SURFACE : MTR²

v2.13

Code:	Dwg. No.	Description	Size	Pcs.	spare		remarks
M200	*M200*	Sidewall-corner-purlin U.80x40x2,0	4.496	**41**	b		punching pattern ctc 900 mm
M201	*M201*	Sidewall-corner-purlin U.80x40x2,0	4.426	**49**	b		punching pattern ctc 900 mm
		SIDEWALL PURLIN					**EXPEDITIE :**
		MAGNELIS S250GD+ZM					Code op gording geprint

appendix 2b

Order list for aluminium components from aluminium supplier BOAL systems.



BOAL SYSTEMS

MATERIAALSPECIFICATIE

Uitgewerkt door M. (Mehrdad) Moheb op 29-03-2019

Versie	2
Pagina	1 / 2

Klant	VB Greenhouses BV
Klant projectnaam	Mighty Vine USA - 0719001
Klant projectnummer	
BOAL opdracht	129260
BOAL opdrachtorder	4 - Dek
Klantreferentie	190038

Aanvang laden	Week 15
Leveringsvoorwaarde(n)	EXW - Af Fabriek: 's-Gravenzande
Afhaaladres	

Regel	Artikel	Aantal	Eenheid	Omschrijving
10	IGROEDENVERB-1	6.130	Stuk(s)	Momentvasteroedenverbinding met inbus
30	IBROEDENOKCLIP-1	2.300	Stuk(s)	Roede-nok borgclip zwaar
40	IR02827/0050	34.150	Stuk(s)	Gootrubber (IR2827) L=50mm
50	IP07600/1125	11.600	Stuk(s)	Afdekstrip (A7600) L=1125mm (PVC)
60	NK50343/9000	703	Stuk(s)	Nok (B50343) L=9000mm
70	NK50343/5300	30	Stuk(s)	Nok (B50343) L=5300mm
80	MA05499/0080-1	750	Stuk(s)	Nokverbinding (B5499) L=80mm - onder geschroefd
90	DR51101/2382*	12.250	Stuk(s)	Dekroede 50 (B51101) 4.50m VWL Dekroede bewerking: Standaard Dr_klikker: Met roedeklikker Extra_gat: 0 stuk(s)
100	DR50444/2382*	10	Stuk(s)	Reparatieroede 50 (B50444) 4.50m VWL links
110	DR50444/2382*R	10	Stuk(s)	Reparatieroede 50 (B50444) 4.50m VWL rechts
120	IP04900/2555	20	Stuk(s)	Reparatiestrip (A4900) L=2555mm (PVC)
130	IBDVS-K	115	Stuk(s)	Dakvlakschoringkabel (compleet) L=5100mm
140	MA01121/0050	30	Stuk(s)	Bevestiging-GNG/DVS (B1121) L= 50mm
150	IBBOUTM8X20ZKK	250	Stuk(s)	Zeskantkopbout M8x20 (DIN 933) RVS
160	IBBORGMOERM8	250	Stuk(s)	Borgmoer M8 (DIN 985) RVS
170	IBCARRINGRVSM8	250	Stuk(s)	Carrosseriering M8 (DIN 9021) RVS
180	R05396/3X1125E	1.350	Stuk(s)	Scharnier E (B5396) 3x1112 rail
190	R50451/3X1125F4	1.350	Stuk(s)	Dorpel F (B50451) 3 x 1112 (4 opdrukkers)
200	LR50776/1386	2.700	Stuk(s)	Tussenstijl (B50776) tbv 1400 F-raam
210	LR50772/1395L-L	1.350	Stuk(s)	Zijstijl (B50772) L=1395mm - Links
220	LR50772/1395R-L	1.350	Stuk(s)	Zijstijl (B50772) L=1395mm - Rechts
230	LR05440/0028	2.700	Stuk(s)	Luchtraamborging (B5440) L=28mm
240	LR50538/0030	5.600	Stuk(s)	Opdrukschuif (B50538) L=30mm
250	IBPLTSCRF4,8X32	5.600	Stuk(s)	Parker 4,8x32 DIN 7981C-SQ
260	IBPLTSCRF4,8X13	5.600	Stuk(s)	Parker 4,8x13 DIN 7981+SQ A2
270	IBPARKER5,5X13-1	2.800	Stuk(s)	Parker 5,5x13 DIN 7981CH A2 RVS
280	IR02827/0050	8.300	Stuk(s)	Gootrubber (IR2827) L=50mm
290	IBSPLITPEN6X42	5.950	Stuk(s)	Splitpen 6x42
300	KV50572/3X1125	1.350	Stuk(s)	Kalf (B50572) 3-Ruits HoH=1125mm
320	IBKALFVEERLIP	5.500	Stuk(s)	Kalfveer met lip doorgezet RVS
330	R05396/6X0562E	58	Stuk(s)	Scharnier E (B5396) 6x549 rail
340	R50451/6X0562F4	58	Stuk(s)	Dorpel F (B50451) 6 x 549 (4 opdrukkers)
350	LR50776/1386	290	Stuk(s)	Tussenstijl (B50776) tbv 1400 F-raam
360	LR50772/1395L-L	58	Stuk(s)	Zijstijl (B50772) L=1395mm - Links
370	LR50772/1395R-L	58	Stuk(s)	Zijstijl (B50772) L=1395mm - Rechts
380	LR05440/0028	120	Stuk(s)	Luchtraamborging (B5440) L=28mm
390	LR50538/0030	240	Stuk(s)	Opdrukschuif (B50538) L=30mm
400	IBPLTSCRF4,8X32	600	Stuk(s)	Parker 4,8x32 DIN 7981C-SQ
410	IBPLTSCRF4,8X13	250	Stuk(s)	Parker 4,8x13 DIN 7981+SQ A2
420	IBPARKER5,5X13-1	300	Stuk(s)	Parker 5,5x13 DIN 7981CH A2 RVS

BOAL Systemen B.V.
Marie Curiestraat 3 • NL - 2691 HC 's-Gravenzande • **I** www.boalsystems.com • **T** +31 (0) 174 316 100 • **E** salesbs@boalgroup.com
KvK 27216232 • **BTW** NL006077857B02 • **Bank** ABN AMRO Bank Rotterdam • **IBAN** NL16 ABNA 0637 9845 01 • **BIC** ABNANL2A

MATERIAALSPECIFICATIE

Uitgewerkt door M. (Mehrdad) Moheb op 29-03-2019

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Klant	VB Greenhouses BV	BOAL opdracht	129260
Klant projectnaam	Mighty Vine USA - 0719001	BOAL opdrachtorder	4 - Dek

Regel	Artikel	Aantal	Eenheid	Omschrijving
430	IR02827/0050	700	Stuk(s)	Gootrubber (IR2827) L=50mm
440	KV50572/2X0562	174	Stuk(s)	Kalf (B50572) 2-Ruits HoH=562mm
460	IBKALFVEERLIP	550	Stuk(s)	Kalfveer met lip doorgezet RVS
470	R05396/2X0562E	58	Stuk(s)	Scharnier E (B5396) 2x549 rail
480	R50451/2X0562F2	58	Stuk(s)	Dorpel F (B50451) 2 x 549 (2 opdrukkers)
490	LR50776/1386	58	Stuk(s)	Tussenstijl (B50776) tbv 1400 F-raam
500	LR50772/1395L-L	58	Stuk(s)	Zijstijl (B50772) L=1395mm - Links
510	LR50772/1395R-L	58	Stuk(s)	Zijstijl (B50772) L=1395mm - Rechts
520	LR05440/0028	120	Stuk(s)	Luchtraamborging (B5440) L=28mm
530	LR50538/0030	120	Stuk(s)	Opdrukschuif (B50538) L=30mm
540	IBPLTSCRF4,8X32	120	Stuk(s)	Parker 4,8x32 DIN 7981C-SQ
550	IBPLTSCRF4,8X13	250	Stuk(s)	Parker 4,8x13 DIN 7981+SQ A2
560	IBPARKER5,5X13-1	60	Stuk(s)	Parker 5,5x13 DIN 7981CH A2 RVS
570	IR02827/0050	250	Stuk(s)	Gootrubber (IR2827) L=50mm
590	KV50572/2X0562	58	Stuk(s)	Kalf (B50572) 2-Ruits HoH=562mm
610	IBKALFVEERLIP	180	Stuk(s)	Kalfveer met lip doorgezet RVS
620	IP06275/1410	3.125	Stuk(s)	Afdekstrip (A6275) L=1410mm (PVC)
630	IP05131-S/1397	3.000	Stuk(s)	Zijstijlstrip (A5131) L=1397mm (PVC) - Smal
640	IP05131-S/1125	4.375	Stuk(s)	Raamstrip (A5131) L=1125mm (PVC) - Smal
650	IR01036/200M	800	Meter(s)	Gootrubber (IR1036)
660	IRNEOPR15X3MM	600	Meter(s)	EPDM-rubber 15 x 3 (zelfklevend)
670	GR50759/4500	106	Stuk(s)	Dilatatieprofiel (B50759) L=4500mm
680	MAKOPPEL/50759	110	Stuk(s)	Koppelplaat voor dilatatieprofiel B50759
690	IBSUPTEX4,8X19R	1.200	Stuk(s)	Supertex 4,8x19 ZK DIN7504-K AISI410 R14
700	IBBOUTM6X16ZKK	440	Stuk(s)	Zeskantkopbout M6x16 RVS
710	IBSLUITRINGM6NE	880	Stuk(s)	Sluitring M6 met neopreen ring RVS
720	IBBORGMOERM6	440	Stuk(s)	Borgmoer M6 (DIN 985) RVS
730	IBDILATATIEBEUG	775	Stuk(s)	Beugel voor Gootdilatatie RVS
740	IBDILATATIEVEER	1.550	Stuk(s)	Veer voor Dilatatie - RVS
750	IDMULTISPRAY	6	Stuk(s)	Multispray met Smart Straw
760	IDPROFICLEANER	2	Stuk(s)	Profi-Cleaner ontvetter/reiniger
770	IDMSPOLYMEER	4	Stuk(s)	Lijmkit MAX MS Polymeer
780	IR02665/25M DUN	275	Meter(s)	Dilatatierubber 160-400 nr. 2665 met dunne pijl
790	MA01453/0025	6	Stuk(s)	Verbindingshoek (B1453) L=25mm
830	IBSUPTEX4,8X13	75	Stuk(s)	Supertex 4,8x13 ZK DIN7504-K AISI410
850	RT 3X1125/50451/14 00	2	Stuk(s)	Ramentafel Luchtraam diepte: 1400 millimeter(s)

MATERIAALSPECIFICATIE

Uitgewerkt door M. (Mehrdad) Moheb op 02-04-2019

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Klant	VB Greenhouses BV	Aanvang laden	Week 15
Klant projectnaam	Mighty Vine USA - 0719001	Leveringsvoorwaarde(n)	EXW - Af Fabriek: 's-Gravenzande
Klant projectnummer		**Afhaaladres**	
BOAL opdracht	129260		
BOAL opdrachtorder	5 - Gevels 4mm		
Klantreferentie	190038		

Regel	Artikel	Aantal	Eenheid	Omschrijving
260	GG05570/6000	41	Stuk(s)	Gootregel (B5570) L=6000mm
280	IDAFDEKPLAAT160/40 00	61	Stuk(s)	Afdekplaat gootregel hk-vzg<160 L=4000 mm
340	IBSUPTEX4,8X13	1.250	Stuk(s)	Supertex 4,8x13 ZK DIN7504-K AISI410
350	MA01103/0080	90	Stuk(s)	Koppelstift (B1103) L=80mm
360	VR50533/6000	41	Stuk(s)	Voetregel (B50533) L=6000mm
370	VR50533/0700-1	2	Stuk(s)	Voetregelhoekstuk (B50533) L=700mm - links
380	VR50533/0700-2	2	Stuk(s)	Voetregelhoekstuk (B50533) L=700mm - rechts
520	IRNEOPR50X4X2	700	Stuk(s)	Beglaasrubber 50 x 4 x 2
530	MA05548/0030	210	Stuk(s)	Voetregelbevestiging (B5548) L=30mm
550	IBSUPTEX6,3X25R	20	Stuk(s)	Supertex 6,3x25 ZK DIN7504-K AISI410R16
560	MA01453/0025	2	Stuk(s)	Verbindingshoek (B1453) L=25mm
570	IBBOUTM6X16VKK	10	Stuk(s)	Vierkantkopbout M6x16 RVS
580	IBBORGMOERM6	10	Stuk(s)	Borgmoer M6 (DIN 985) RVS
590	GR50496	225	Stuk(s)	Gevelroede (B50496) Type A - L=6790mm Extra_gat: 0 stuk(s) Glasmaat: 3x 2134 Gr_bew: Gtr Ruiten: 4 stuk(s)
600	GR50496	102	Stuk(s)	Gevelroede (B50496) Type B - L=6790mm Extra_gat: 0 stuk(s) Glasmaat: 2x 2134 + 1615 Gr_bew: Gtr Ruiten: 5 stuk(s)
610	GR50496	106	Stuk(s)	Gevelroede (B50496) L=850mm Extra_gat: 0 stuk(s) Glasmaat: - Gr_bew: Gtr Ruiten: 1 stuk(s)
620	IP06275	350	Stuk(s)	Afdekstrip (A6275) (PVC) L=6813mm
650	IBBOUTM6X12VKK	1.100	Stuk(s)	Vierkantkopbout M6x12 RVS
670	IBBORGMOERM6	1.100	Stuk(s)	Borgmoer M6 (DIN 985) RVS
680	MA50511/0030	350	Stuk(s)	Roede-Voetregelbevestiging E (B50511) L=30mm
690	MA05173/0030-1	430	Stuk(s)	Kikkerplaat (B5173) L=30mm + M6x20VKK
730	SP50918/0736	900	Stuk(s)	Stapelprofiel (B50918) L=736mm met rubber
740	SP50918/0361	85	Stuk(s)	Stapelprofiel (B50918) L=361mm met rubber
860	MA05514/0011	1.000	Stuk(s)	Stapelkoppelstift (B5514) L=11mm
870	MA50314/0011	50	Stuk(s)	Stapelkoppelstift-Half (B50314) L=11mm

MATERIAALSPECIFICATIE

Uitgewerkt door M. (Mehrdad) Moheb op 01-04-2019

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Klant	VB Greenhouses BV	Aanvang laden	Week 16
Klant projectnaam	Mighty Vine USA - 0719001	Leveringsvoorwaarde(n)	EXW - Af Fabriek: 's-Gravenzande
Klant projectnummer		**Afhaaladres**	
BOAL opdracht	129260		
BOAL opdrachtorder	6 - Gevels 16 mm		
Klantreferentie	190038		

Regel	Artikel	Aantal	Eenheid	Omschrijving
10	DH50282/2382-50-L	59	Stuk(s)	Dakhoekroede B50282 4,50m VWL 50mm links Dekroe: 50 Goottype: Vwl
20	DH50282/2382-50-R	59	Stuk(s)	Dakhoekroede B50282 4,50m VWL 50mm rechts Dekroe: 50 Goottype: Vwl
30	IP04899	125	Stuk(s)	Afdekstrip (A4899) (PVC) L=2374mm
40	IRAFDPRP4899/15	120	Stuk(s)	Afdichtprop voor Afdekstrip A4899 L=15mm
50	IDAFDPLNOK-DHR	60	Stuk(s)	Afdekplaatje voor dakhoekroede in nok
60	MA01111/0110	60	Stuk(s)	Verbindingstrip (B1111) L=110mm
70	IBBOUTM6X16HK	125	Stuk(s)	Hamerkopbout M6x16 RVS
150	MAVULBLOKJE-50	120	Stuk(s)	Vulblokje voor Goot-50 en SDP-DHR
180	IBBOUTM6X25HK	125	Stuk(s)	Hamerkopbout M6x25 RVS
200	IBBORGMOERM6	250	Stuk(s)	Borgmoer M6 (DIN 985) RVS
260	IDGEVELPL-SPEC	120	Stuk(s)	Gevelafdekplaat - speciaal (60x DWZ + 60x NDWZ)
400	MA01103/0080	50	Stuk(s)	Koppelstift (B1103) L=80mm
410	VR50544/6000	45	Stuk(s)	Voetregel SDP (B50544) L=6000mm
420	VR50544/0700-1	2	Stuk(s)	Voetregelhoekstuk SDP (B50544) L=700mm - Links
430	VR50544/0700-2	2	Stuk(s)	Voetregelhoekstuk SDP (B50544) L=700mm - Rechts
530	MA05548/0030	250	Stuk(s)	Voetregelbevestiging (B5548) L=30mm
540	IBSPIJKERPLUG	250	Stuk(s)	Spijkerplug 6x40
550	IBSUPTEX6,3X25R	100	Stuk(s)	Supertex 6,3x25 ZK DIN7504-K AISI410R16
560	MA01453/0025	2	Stuk(s)	Verbindingshoek (B1453) L=25mm
570	IBBOUTM6X16VKK	1.000	Stuk(s)	Vierkantkopbout M6x16 RVS
580	IBBORGMOERM6	1.000	Stuk(s)	Borgmoer M6 (DIN 985) RVS
590	GR50264	30	Stuk(s)	Gevelroede SDP (B50264) L=6674mm Extra_gat: 0 stuk(s) Gr_bew: Geen
600	GR50264	58	Stuk(s)	Gevelroede SDP (B50264) L=7189mm Extra_gat: 0 stuk(s) Gr_bew: Dhr
610	GR50264	58	Stuk(s)	Gevelroede SDP (B50264) L=7545mm Extra_gat: 0 stuk(s) Gr_bew: Dhr
620	GR50264	30	Stuk(s)	Gevelroede SDP (B50264) L=6569mm Extra_gat: 1 stuk(s) Gr_bew: Geen
630	GR50264	58	Stuk(s)	Gevelroede SDP (B50264) Type AZ - L=7189mm Extra_gat: 1 stuk(s) Gr_bew: Dhr
640	GR50264	58	Stuk(s)	Gevelroede SDP (B50264) Type AZ - L=7545mm Extra_gat: 1 stuk(s) Gr_bew: Dhr

MATERIAALSPECIFICATIE

Uitgewerkt door M. (Mehrdad) Moheb op 01-04-2019

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Klant	VB Greenhouses BV	BOAL opdracht	129260
Klant projectnaam	Mighty Vine USA - 0719001	BOAL opdrachtorder	6 - Gevels 16 mm

Regel	Artikel	Aantal	Eenheid	Omschrijving
650	IP07103	200	Stuk(s)	Afdekstrip (A7103) (PVC) L=7249mm
660	IP07103	150	Stuk(s)	Afdekstrip (A7103) (PVC) L=7605mm
700	MA50511/0030	350	Stuk(s)	Roede-Voetregelbevestiging E (B50511) L=30mm
720	MA05857/0030-2	350	Stuk(s)	Eengatsplaat (B5857) L=30mm + M6x20VKK
750	SP50754/0866	300	Stuk(s)	Afdichtprofiel (B50754) L=866 mm
790	IBSUPTEX4,8X19R	600	Stuk(s)	Supertex 4,8x19 ZK DIN7504-K AISI410 R14
810	SP50926/0890	150	Stuk(s)	Stapelprofiel (B50926) L=890mm
820	MA50541/0006	150	Stuk(s)	Stapelkoppelstift (B50541) L=6mm

MATERIAALSPECIFICATIE

Uitgewerkt door M. (Mehrdad) Moheb op 01-03-2019

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Klant	VB Greenhouses BV	Aanvang laden	Week 12
Klant projectnaam	Mighty Vine USA - 0719001	Leveringsvoorwaarde(n)	EXW - Af Fabriek: 's-Gravenzande
Klant projectnummer		Afhaaladres	
BOAL opdracht	129260		
BOAL opdrachtorder	1 - Goten		
Klantreferentie	190012		

Regel	**Artikel**	**Aantal**	**Eenheid**	**Omschrijving**
10	GT50505	26	Stuk(s)	Goot (B50505) venlo VWL-50 Type A1 - L=5625mm

Specificatie			
IBHUCKNAGEL8-10	104	Stuk(s)	Hucknagel MGLP B 8-10
GT50523/0100	52	Stuk(s)	Bovenkoppeling goot (B50523) L=100mm
GT50745/0310	104	Stuk(s)	Koppelstrip (B50745) L=310mm gemonteerd
GT50275/0130K	52	Stuk(s)	Gootconsole (B50275) type K L=130 mm
GT50276/0130K	52	Stuk(s)	Gootconsole (B50276) type K L=130 mm

Regel	**Artikel**	**Aantal**	**Eenheid**	**Omschrijving**
20	GT50505	2	Stuk(s)	Goot (B50505) venlo VWL-50 Type A2 - L=5625mm

Specificatie			
IBHUCKNAGEL8-10	12	Stuk(s)	Hucknagel MGLP B 8-10
GT50523/0100	4	Stuk(s)	Bovenkoppeling goot (B50523) L=100mm
GT50745/0310	8	Stuk(s)	Koppelstrip (B50745) L=310mm gemonteerd
GT50275/0130K	6	Stuk(s)	Gootconsole (B50275) type K L=130 mm
GT50276/0130K	6	Stuk(s)	Gootconsole (B50276) type K L=130 mm

Regel	**Artikel**	**Aantal**	**Eenheid**	**Omschrijving**
30	GT50505	1	Stuk(s)	Goot (B50505) venlo VWL-50 Type A3 - L=5625mm

Specificatie			
IBHUCKNAGEL8-10	5	Stuk(s)	Hucknagel MGLP B 8-10
GT50275/0050D	1	Stuk(s)	Gootconsole (B50275) type D L=50 mm
GT50276/0050D	1	Stuk(s)	Gootconsole (B50276) type D L=50 mm
GT50523/0100	2	Stuk(s)	Bovenkoppeling goot (B50523) L=100mm
GT50745/0310	4	Stuk(s)	Koppelstrip (B50745) L=310mm gemonteerd
GT50275/0130K	2	Stuk(s)	Gootconsole (B50275) type K L=130 mm
GT50276/0130K	2	Stuk(s)	Gootconsole (B50276) type K L=130 mm

Regel	**Artikel**	**Aantal**	**Eenheid**	**Omschrijving**
40	GT50505	1	Stuk(s)	Goot (B50505) venlo VWL-50 Type A4 - L=5625mm

Specificatie			
IBHUCKNAGEL8-10	6	Stuk(s)	Hucknagel MGLP B 8-10
GT50523/0100	2	Stuk(s)	Bovenkoppeling goot (B50523) L=100mm
GT50745/0310	4	Stuk(s)	Koppelstrip (B50745) L=310mm gemonteerd
GT50275/0140J	3	Stuk(s)	Gootconsole (B50275) type J L=140 mm
GT50276/0140J	3	Stuk(s)	Gootconsole (B50276) type J L=140 mm

MATERIAALSPECIFICATIE

Uitgewerkt door M. (Mehrdad) Moheb op 01-03-2019
Versie 3
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Klant	VB Greenhouses BV	BOAL opdracht	129260
Klant projectnaam	Mighty Vine USA - 0719001	BOAL opdrachtorder	1 - Goten

Regel	Artikel	Aantal	Eenheid	Omschrijving
50	GT50505	578	Stuk(s)	Goot (B50505) venlo VWL-50 Type B1 - L=9000mm

Specificatie

IBHUCKNAGEL8-10	2.312	Stuk(s)	Hucknagel MGLP B 8-10
GT50523/0100	578	Stuk(s)	Bovenkoppeling goot (B50523) L=100mm
GT50745/0310	1.156	Stuk(s)	Koppelstrip (B50745) L=310mm gemonteerd
GT50275/0130K	1.156	Stuk(s)	Gootconsole (B50275) type K L=130 mm
GT50276/0130K	1.156	Stuk(s)	Gootconsole (B50276) type K L=130 mm

Regel	Artikel	Aantal	Eenheid	Omschrijving
60	GT50505	46	Stuk(s)	Goot (B50505) venlo VWL-50 Type B2 - L=9000mm

Specificatie

IBHUCKNAGEL8-10	368	Stuk(s)	Hucknagel MGLP B 8-10
GT50523/0100	46	Stuk(s)	Bovenkoppeling goot (B50523) L=100mm
GT50745/0310	92	Stuk(s)	Koppelstrip (B50745) L=310mm gemonteerd
GT50275/0130K	184	Stuk(s)	Gootconsole (B50275) type K L=130 mm
GT50276/0130K	184	Stuk(s)	Gootconsole (B50276) type K L=130 mm

Regel	Artikel	Aantal	Eenheid	Omschrijving
70	GT50505	23	Stuk(s)	Goot (B50505) venlo VWL-50 Type B3 - L=9000mm

Specificatie

IBHUCKNAGEL8-10	138	Stuk(s)	Hucknagel MGLP B 8-10
GT50275/0050D	46	Stuk(s)	Gootconsole (B50275) type D L=50 mm
GT50276/0050D	46	Stuk(s)	Gootconsole (B50276) type D L=50 mm
GT50523/0100	23	Stuk(s)	Bovenkoppeling goot (B50523) L=100mm
GT50745/0310	46	Stuk(s)	Koppelstrip (B50745) L=310mm gemonteerd
GT50275/0130K	46	Stuk(s)	Gootconsole (B50275) type K L=130 mm
GT50276/0130K	46	Stuk(s)	Gootconsole (B50276) type K L=130 mm

Regel	Artikel	Aantal	Eenheid	Omschrijving
80	GT50505	23	Stuk(s)	Goot (B50505) venlo VWL-50 Type B4 - L=9000mm

Specificatie

IBHUCKNAGEL8-10	184	Stuk(s)	Hucknagel MGLP B 8-10
GT50523/0100	23	Stuk(s)	Bovenkoppeling goot (B50523) L=100mm
GT50745/0310	46	Stuk(s)	Koppelstrip (B50745) L=310mm gemonteerd
GT50275/0140J	92	Stuk(s)	Gootconsole (B50275) type J L=140 mm
GT50276/0140J	92	Stuk(s)	Gootconsole (B50276) type J L=140 mm

MATERIAALSPECIFICATIE

Uitgewerkt door M. (Mehrdad) Moheb op 01-03-2019

Versie 3
Pagina 3 / 4

Klant	VB Greenhouses BV	BOAL opdracht	129260
Klant projectnaam	Mighty Vine USA - 0719001	BOAL opdrachtorder	1 - Goten

Regel	Artikel	Aantal	Eenheid	Omschrijving
90	GT50506-E	52	Stuk(s)	Goot (B50506) venlo VWL-50 Type E1 - L=8848mm

Specificatie

IBHUCKNAGEL8-10	520	Stuk(s)	Hucknagel MGLP B 8-10
GT50275/0040F	52	Stuk(s)	Gootconsole (B50275) type F L=40 mm
GT50276/0040F	52	Stuk(s)	Gootconsole (B50276) type F L=40 mm
GT50275/0050D	104	Stuk(s)	Gootconsole (B50275) type D L=50 mm
GT50640/0110	52	Stuk(s)	8-Gatsplaat (B50640) DVS/GNG L=110 mm
GT50276/0050D	104	Stuk(s)	Gootconsole (B50276) type D L=50 mm
GT50275/0130K	52	Stuk(s)	Gootconsole (B50275) type K L=130 mm
GT50276/0130K	52	Stuk(s)	Gootconsole (B50276) type K L=130 mm
GT50275/0155G	52	Stuk(s)	Gootconsole (B50275) type G L=155 mm
GT50276/0155G	52	Stuk(s)	Gootconsole (B50276) type G L=155 mm
GTKOLOMAFVOER-VWL+HWD	52	Stuk(s)	Kolomafvoer aan VWL-goot met hemelwaterdoorvoer
GTAFDPRBOVWL-50	104	Stuk(s)	Afdichtprop voor goot VWL-50 - boven

Regel	Artikel	Aantal	Eenheid	Omschrijving
100	GT50506-E	4	Stuk(s)	Goot (B50506) venlo VWL-50 Type E2 - L=8848mm

Specificatie

IBHUCKNAGEL8-10	48	Stuk(s)	Hucknagel MGLP B 8-10
GT50275/0040F	4	Stuk(s)	Gootconsole (B50275) type F L=40 mm
GT50276/0040F	4	Stuk(s)	Gootconsole (B50276) type F L=40 mm
GT50275/0050D	8	Stuk(s)	Gootconsole (B50275) type D L=50 mm
GT50276/0050D	8	Stuk(s)	Gootconsole (B50276) type D L=50 mm
GT50275/0130K	12	Stuk(s)	Gootconsole (B50275) type K L=130 mm
GT50276/0130K	12	Stuk(s)	Gootconsole (B50276) type K L=130 mm
GT50275/0155G	4	Stuk(s)	Gootconsole (B50275) type G L=155 mm
GT50276/0155G	4	Stuk(s)	Gootconsole (B50276) type G L=155 mm
GTKOLOMAFVOER-VWL+HWD	4	Stuk(s)	Kolomafvoer aan VWL-goot met hemelwaterdoorvoer
GTAFDPRBOVWL-50	8	Stuk(s)	Afdichtprop voor goot VWL-50 - boven

Regel	Artikel	Aantal	Eenheid	Omschrijving
110	GT50506-E	2	Stuk(s)	Goot (B50506) venlo VWL-50 Type E3 - L=8848mm

Specificatie

IBHUCKNAGEL8-10	26	Stuk(s)	Hucknagel MGLP B 8-10
GT50275/0040F	2	Stuk(s)	Gootconsole (B50275) type F L=40 mm
GT50276/0040F	2	Stuk(s)	Gootconsole (B50276) type F L=40 mm
GT50275/0050D	2	Stuk(s)	Gootconsole (B50275) type D L=50 mm
GT50276/0050D	2	Stuk(s)	Gootconsole (B50276) type D L=50 mm
GT50275/0155G	2	Stuk(s)	Gootconsole (B50275) type G L=155 mm
GT50276/0155G	2	Stuk(s)	Gootconsole (B50276) type G L=155 mm
GT50275-U	6	Stuk(s)	Gootconsole (B50275) + uitkap roedeklem Type J1 - L=140 mm
GT50276-U	6	Stuk(s)	Gootconsole (B50276) + uithap roedeklem Type J1 - L=140 mm
GT50275/0120E1	2	Stuk(s)	Gootconsole (B50275) type E met uithap L=120 mm
GT50276/0120E1	2	Stuk(s)	Gootconsole (B50276) type E met uithap L=120 mm
GTKOLOMAFVOER-VWL+HWD	2	Stuk(s)	Kolomafvoer aan VWL-goot met hemelwaterdoorvoer
GTAFDPRBOVWL-50	4	Stuk(s)	Afdichtprop voor goot VWL-50 - boven

MATERIAALSPECIFICATIE

Uitgewerkt door M. (Mehrdad) Moheb op 01-03-2019
Versie 3
Pagina 4 / 4

Klant	VB Greenhouses BV	BOAL opdracht	129260
Klant projectnaam	Mighty Vine USA - 0719001	BOAL opdrachtorder	1 - Goten

Regel	Artikel	Aantal	Eenheid	Omschrijving
120	GT50506-E	2	Stuk(s)	Goot (B50506) venlo VWL-50 Type E4 - L=8848mm

Specificatie			
IBHUCKNAGEL8-10	26	Stuk(s)	Hucknagel MGLP B 8-10
GT50275/0040F	2	Stuk(s)	Gootconsole (B50275) type F L=40 mm
GT50276/0040F	2	Stuk(s)	Gootconsole (B50276) type F L=40 mm
GT50275/0050D	2	Stuk(s)	Gootconsole (B50275) type D L=50 mm
GT50276/0050D	2	Stuk(s)	Gootconsole (B50276) type D L=50 mm
GT50275/0155G	2	Stuk(s)	Gootconsole (B50275) type G L=155 mm
GT50276/0155G	2	Stuk(s)	Gootconsole (B50276) type G L=155 mm
GT50275/0120E1	6	Stuk(s)	Gootconsole (B50275) type E met uithap L=120 mm
GT50276/0120E1	6	Stuk(s)	Gootconsole (B50276) type E met uithap L=120 mm
GT50275/0130K1	2	Stuk(s)	Gootconsole (B50275) type K met uithap L=130 mm
GT50276/0130K1	2	Stuk(s)	Gootconsole (B50276) type K met uithap L=130 mm
GTKOLOMAFVOER-VWL+HWD	2	Stuk(s)	Kolomafvoer aan VWL-goot met hemelwaterdoorvoer
GTAFDPRBOVWL-50	4	Stuk(s)	Afdichtprop voor goot VWL-50 - boven

150	GT50275/0050D	4	Stuk(s)	Gootconsole (B50275) type D L=50 mm
160	GT50276/0050D	4	Stuk(s)	Gootconsole (B50276) type D L=50 mm
170	GT50275/0130K	6	Stuk(s)	Gootconsole (B50275) type K L=130 mm
180	GT50276/0130K	6	Stuk(s)	Gootconsole (B50276) type K L=130 mm
230	MA05494/0326	728	Stuk(s)	Gootkoppeling (B5494) L=326mm
240	IBSUPTEX6,3X25R	6.100	Stuk(s)	Supertex 6,3x25 ZK DIN7504-K AISI410R16
250	IBPARKER7,2X21R	3.150	Stuk(s)	Parker 7,2x21 DIN 7976C A2 R19 RVS
270	IDZEECONNECTKIT	192	Stuk(s)	Zee-connect kit (netto)
280	MA01121/0050	30	Stuk(s)	Bevestiging-GNG/DVS (B1121) L= 50mm
290	IBBOUTM8X25ZKK	7.400	Stuk(s)	Zeskantkopbout M8x25 (DIN 933) RVS
300	IBBOUTM8X40ZKK	250	Stuk(s)	Zeskantkopbout M8x40 RVS
330	IBMOERM8-C	7.650	Stuk(s)	Moer M8 RVS + coating
410	GTOVLSCHOT/VWL	58	Stuk(s)	Overloopschot voor goot VWL
430	IBSUPTEX6,3X25R	400	Stuk(s)	Supertex 6,3x25 ZK DIN7504-K AISI410R16
440	IDPLWB-VWL/0030	58	Stuk(s)	Waterbak voor goot (VWL) L=30mm met omgezette rand
460	GT50657/6000	40	Stuk(s)	Waterkering (B50657) L=6000mm + rubber
470	MA01103/0080	41	Stuk(s)	Koppelstift (B1103) L=80mm
480	IBSUPTEX4,8X13	950	Stuk(s)	Supertex 4,8x13 ZK DIN7504-K AISI410

appendix 2c-1

Calculation of the required gable glass by VB.

Gable glass

REVISIE 0

	TKN
date	5-8-2018
project	Mighty Vine
adress	Rochelle
Revision	**0**

Glass type	Code	Length	Width	Total	total m^2
4mm single tempered glass 89%	A	2134 mm	735 mm	856 st	1343 m^2
4mm single tempered glass 89%	B	2134 mm	360 mm	80 st	61 m^2
4mm single tempered glass 89%	C	320 mm	735 mm	249 st	59 m^2
4mm single tempered glass 89%	D	320 mm	360 mm	44 st	5 m^2
4mm single tempered glass 89%	E	840 mm	314 mm	110 st	29 m^2
4mm single tempered glass 89%	F	1614 mm	735 mm	55 st	65 m^2
4mm single tempered glass 89%	G	320 mm	167 mm	3 st	m^2
4mm single tempered glass 89%	H	2134 mm	167 mm	7 st	2 m^2
				total m^2	**1565 m^2**

appendix 2c-2

Calculation of the required deck glass by VB.

Roof glass

REVISIE 0

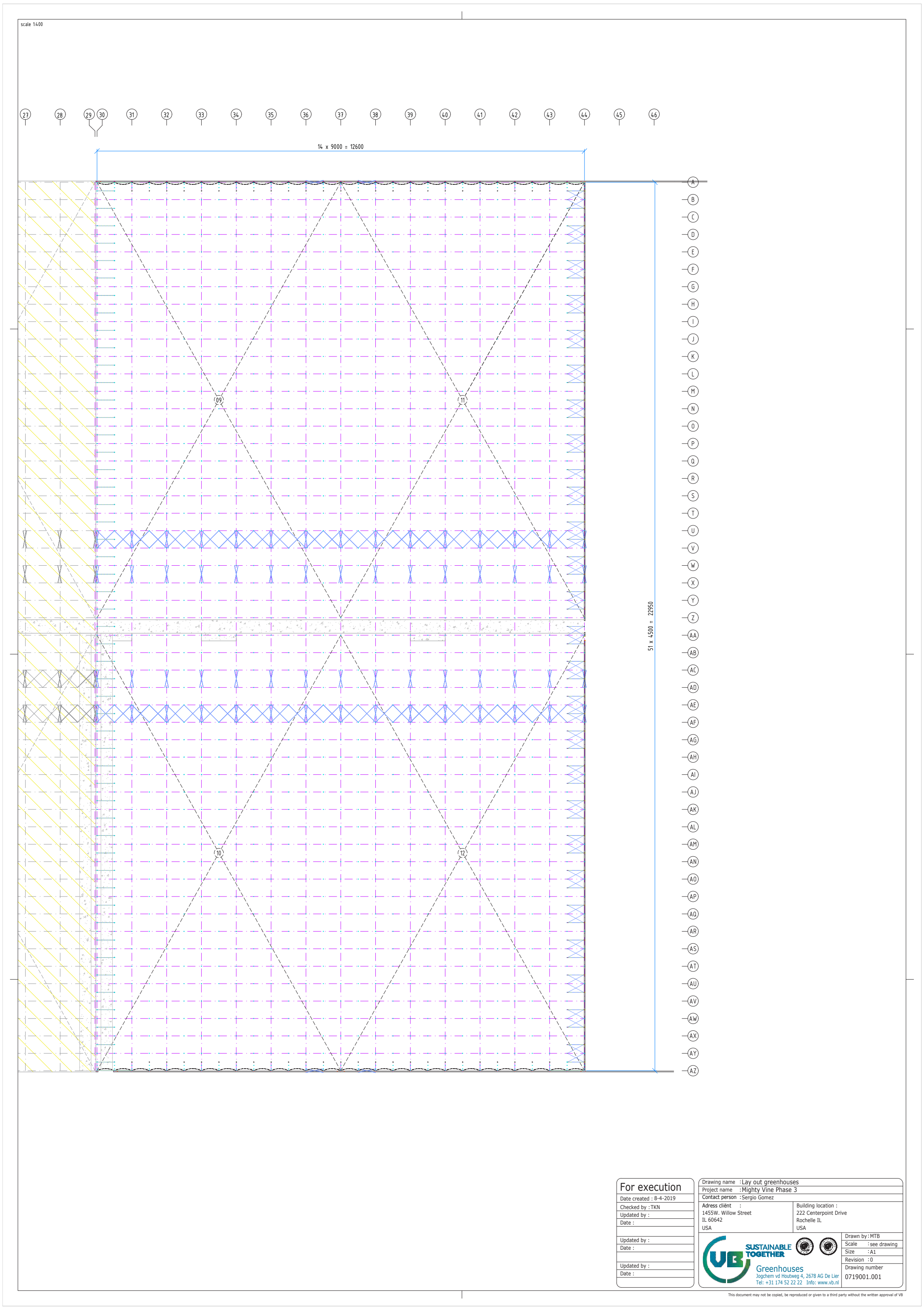
TKN

date 5-8-2018
project Mighty Vine
adress Rochelle
Revision **0**

Glass type	Code	Length	Width	Total	total m²
70% haze and 2x AR treatment	A	2382 mm	1120 mm	6797 st	18134 m²
70% haze and 2x AR treatment	B	2382 mm	558 mm	1028 st	1367 m²
70% haze and 2x AR treatment	C	1400 mm	549 mm	463 st	356 m²
70% haze and 2x AR treatment	D	995 mm	558 mm	463 st	257 m²
70% haze and 2x AR treatment	E	1400 mm	1112 mm	4113 st	6403 m²
70% haze and 2x AR treatment	F	995 mm	1120 mm	4113 st	4583 m²
70% haze and 2x AR treatment	G	2382 mm	250 mm	117 st	70 m²
				total m²	**31169 m²**

appendix 3-1

MightyVine phase 3 general lay-out by VB.



For execution
Date created : 8-4-2019
Checked by : TKN
Updated by :
Date :
Updated by :
Date :
Updated by :
Date :

Drawing name : Lay out greenhouses
Project name : Mighty Vine Phase 3
Contact person : Sergio Gomez

Adress cliënt :
1455W. Willow Street
IL 60642
USA

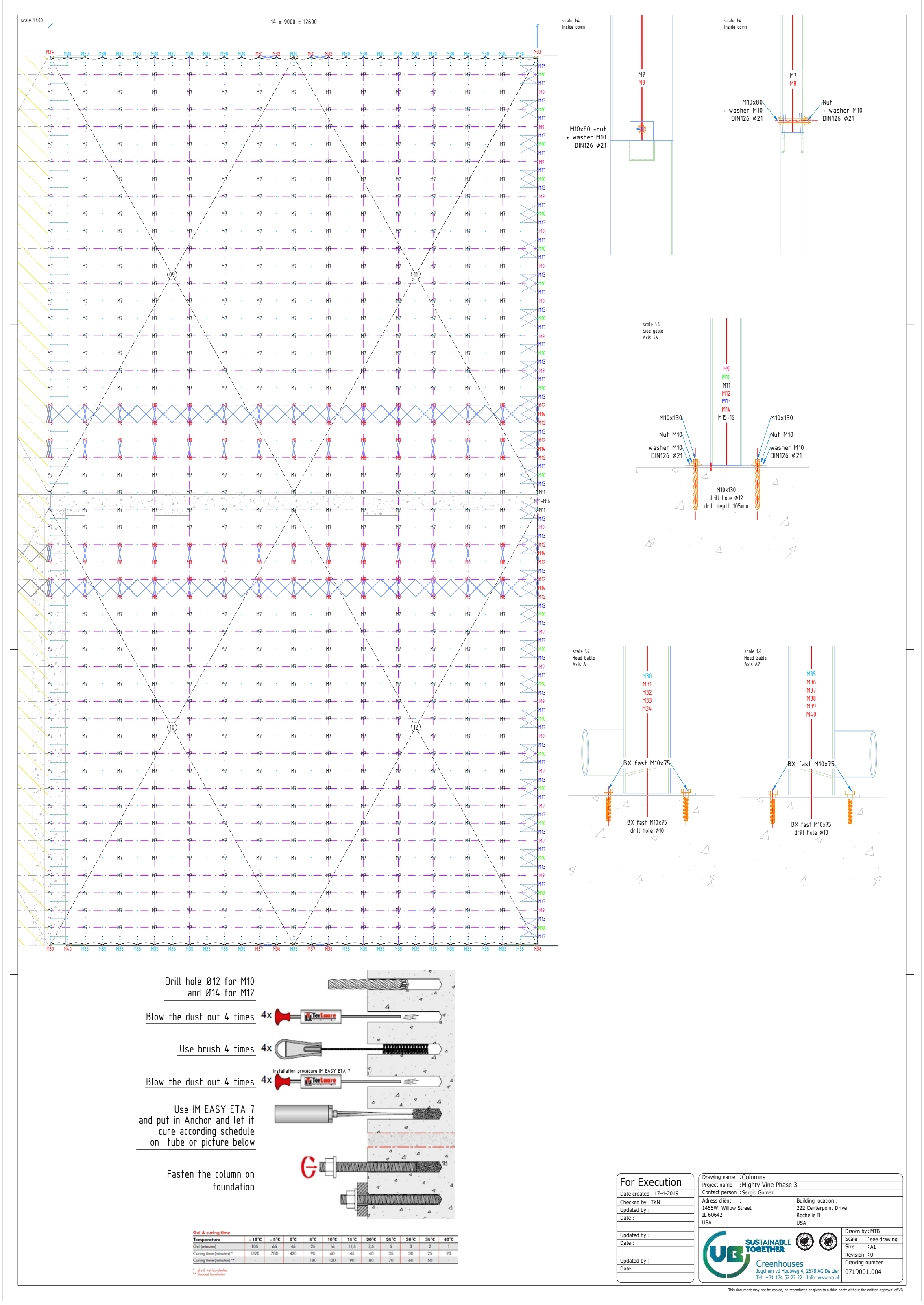
Building location :
222 Centerpoint Drive
Rochelle IL
USA

VB Greenhouses
Jogchem vd Houtweg 4, 2678 AG De Lier
Tel: +31 174 52 22 22 Info: www.vb.nl

Drawn by : MTB
Scale : see drawing
Size : A1
Revision : 0
Drawing number
0719001.001

appendix 3-2

MightyVine phase 3 column lay-out by VB.



Drill hole Ø12 for M10
and Ø14 for M12

Blow the dust out 4 times

Use brush 4 times

Blow the dust out 4 times

Use IM EASY ETA 7
and put in Anchor and let it
cure according schedule
on tube or picture below

Fasten the column on
foundation

Gel & curing time

Temperature	- 10°C	- 5°C	0°C	5°C	10°C	15°C	20°C	25°C	30°C	35°C	40°C
Gel (minutes)	105	65	45	25	16	11,5	7,5	5	3	2	1
Curing time (minutes) *	1320	780	420	90	60	45	40	35	30	25	20
Curing time (minutes) **	-	-	-	180	120	90	80	70	60	50	-

* dry & wet boreholes
** flooded boreholes

For Execution
Date created : 17-4-2019
Checked by : TKN
Updated by :
Date :
Updated by :
Date :
Updated by :
Date :

Drawing name : Columns
Project name : Mighty Vine Phase 3
Contact person : Sergio Gomez

Adress cliënt :
1455W. Willow Street
IL 60642
USA

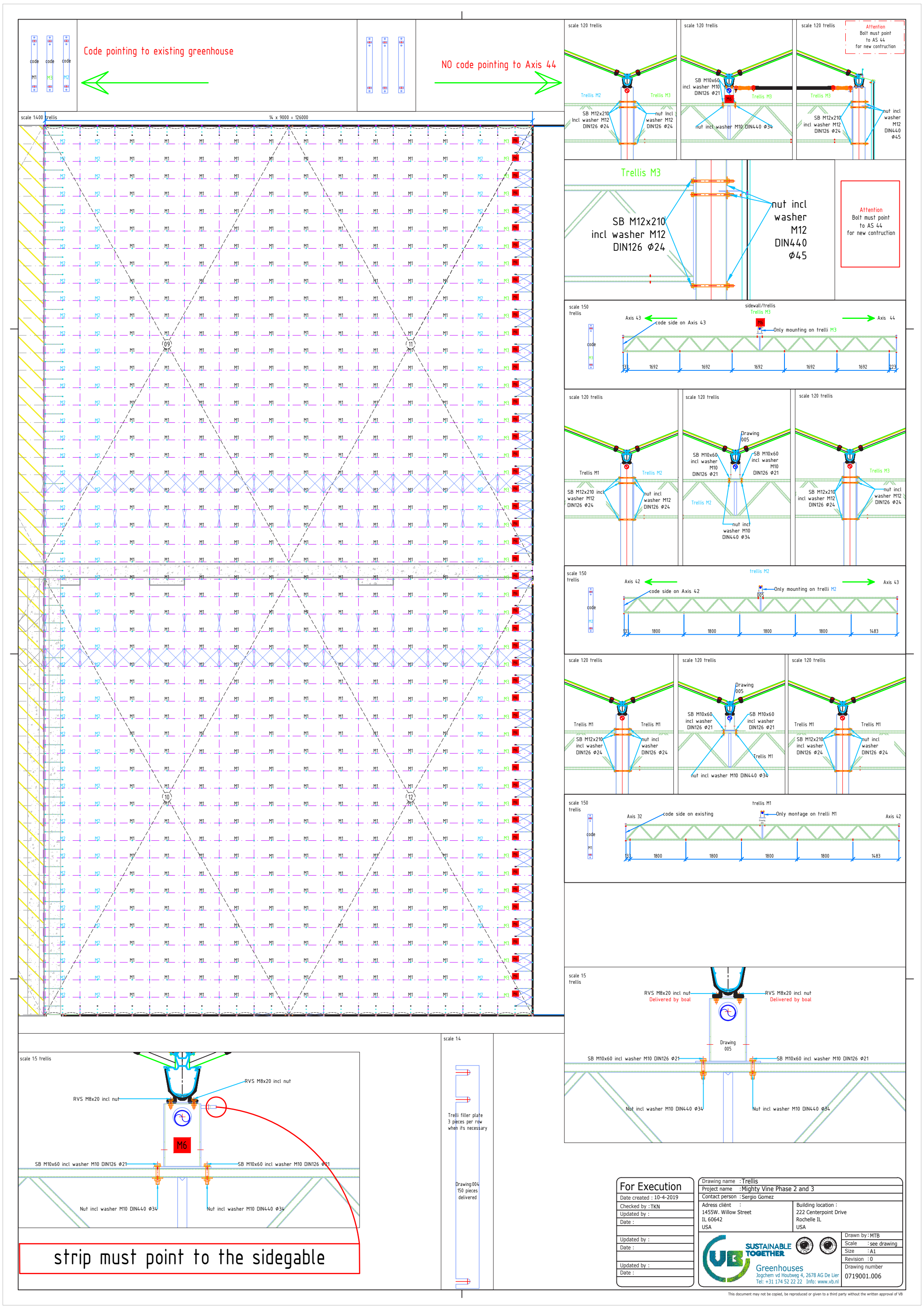
Building location :
222 Centerpoint Drive
Rochelle IL
USA

SUSTAINABLE TOGETHER
Greenhouses
Jogchem vd Houtweg 4, 2678 AG De Lier
Tel: +31 174 52 22 22 Info: www.vb.nl

Drawn by : MTB
Scale : see drawing
Size : A1
Revision : 0
Drawing number
0719001.004

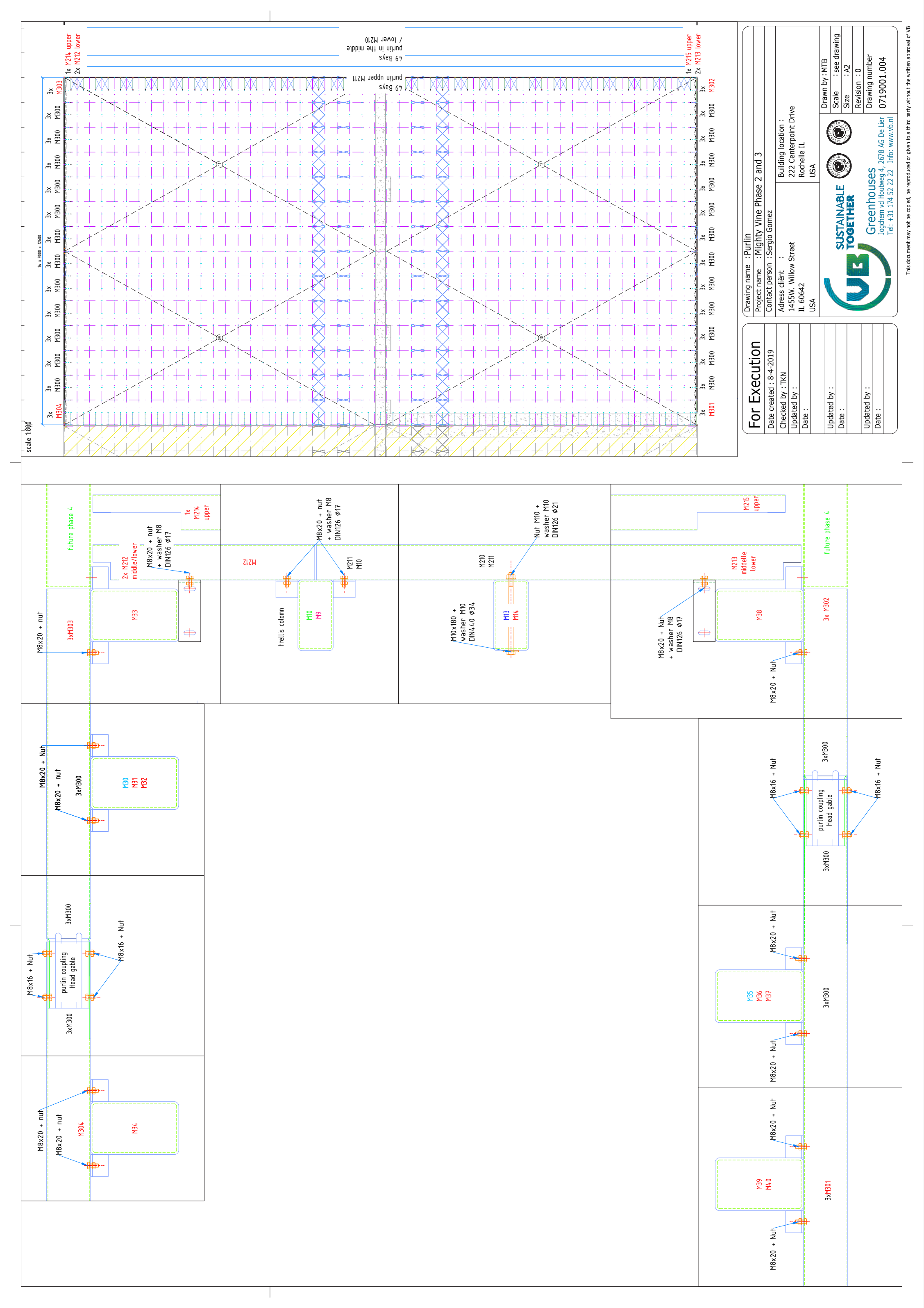
appendix 3-3

MightyVine phase 3 trellis lay-out by VB.



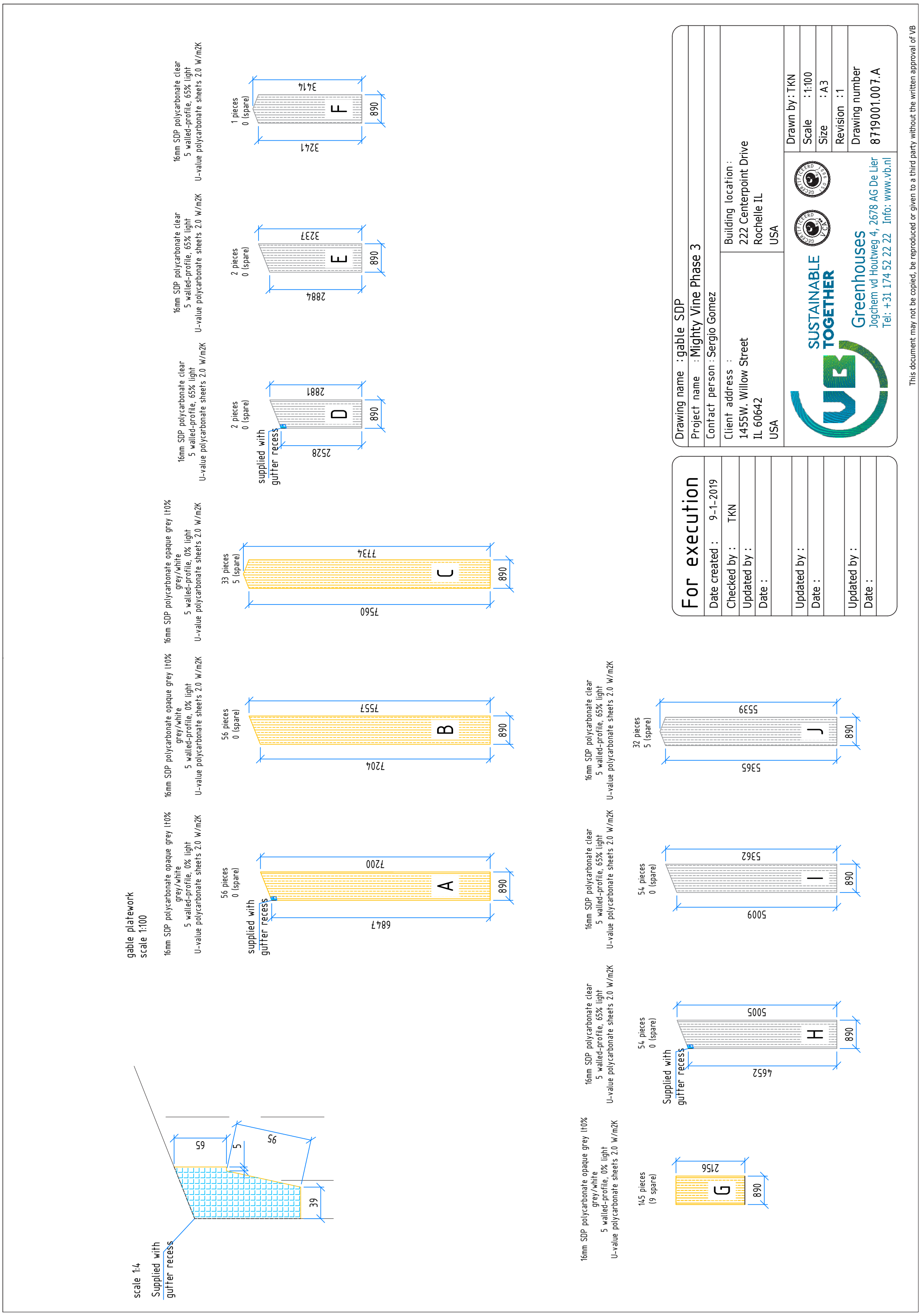
appendix 3-4

MightyVine phase 3 purlin lay-out by VB.



appendix 3-5

MightyVine phase 3 gables by VB.



For execution
Date created : 9-1-2019
Checked by : TKN
Updated by :
Date :

Updated by :
Date :

Updated by :
Date :

Drawing name : gable SDP
Project name : Mighty Vine Phase 3
Contact person : Sergio Gomez

Client address :
1455W. Willow Street
IL 60642
USA

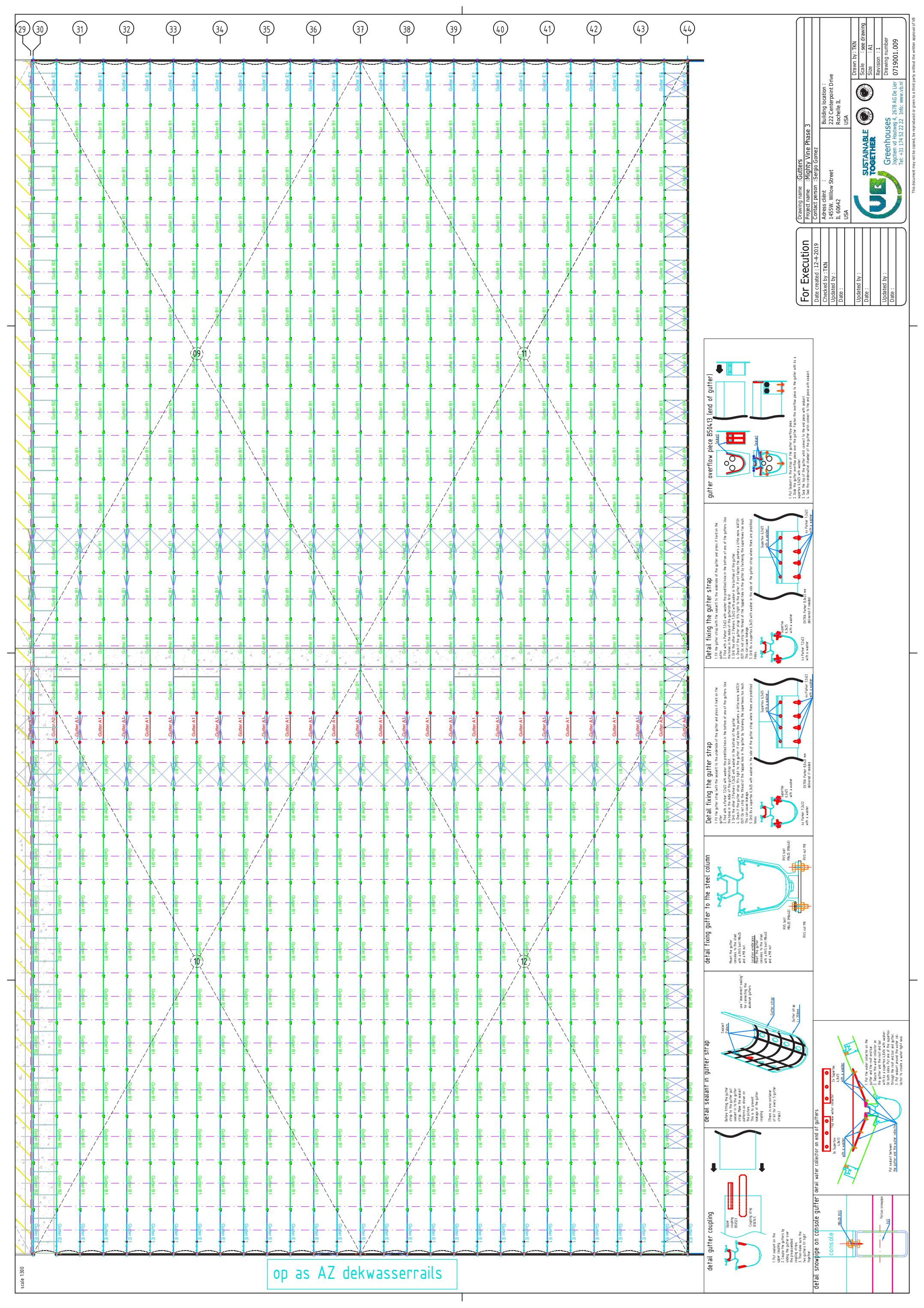
Building location :
222 Centerpoint Drive
Rochelle IL
USA

Greenhouses
Jogchem vd Houtweg 4, 2678 AG De Lier
Tel: +31 174 52 22 22 Info: www.vb.nl

Drawn by : TKN
Scale : 1:100
Size : A3
Revision : 1
Drawing number
8719001.007.A

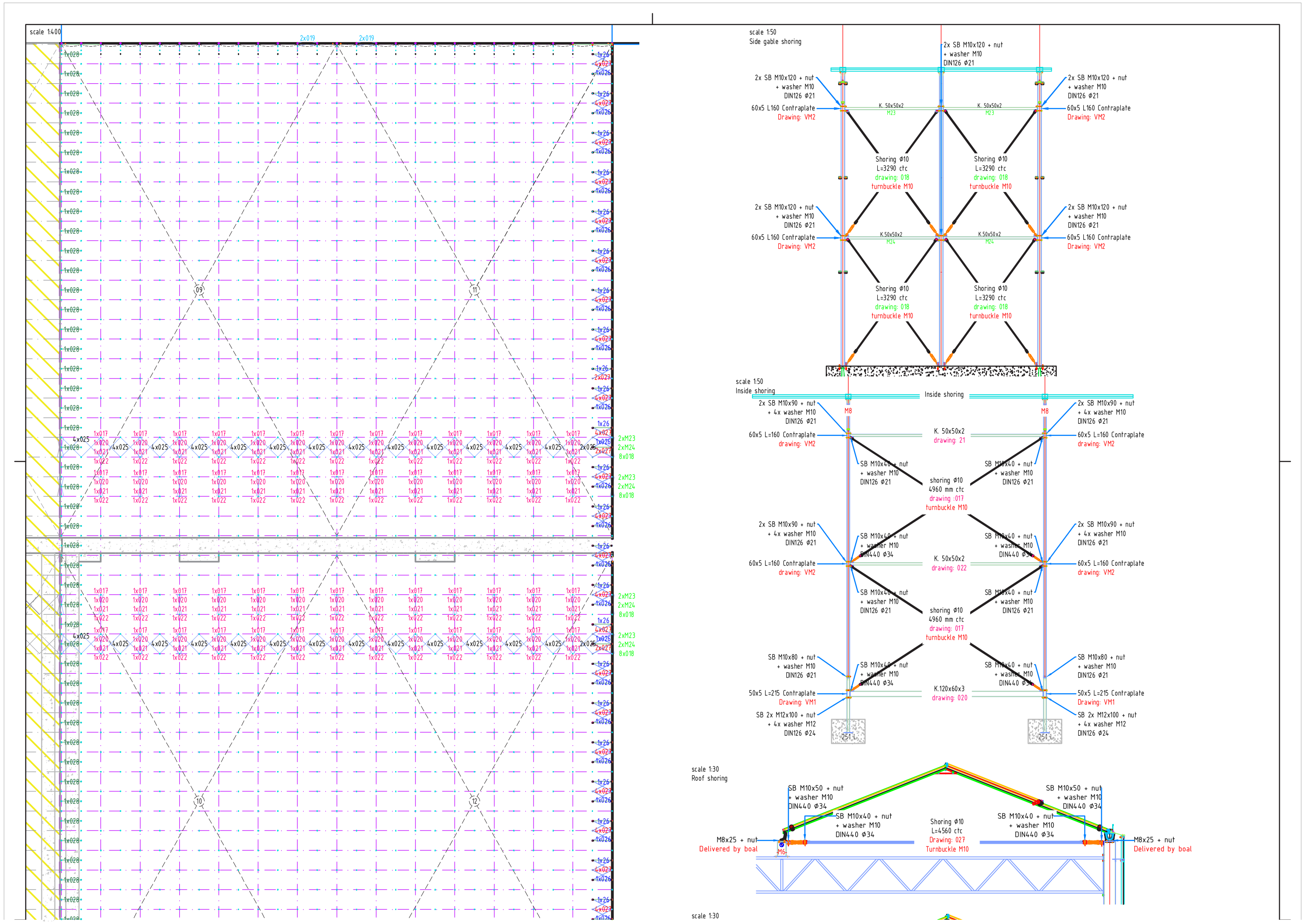
appendix 3-6

MightyVine phase 3 gutter lay-out by VB.



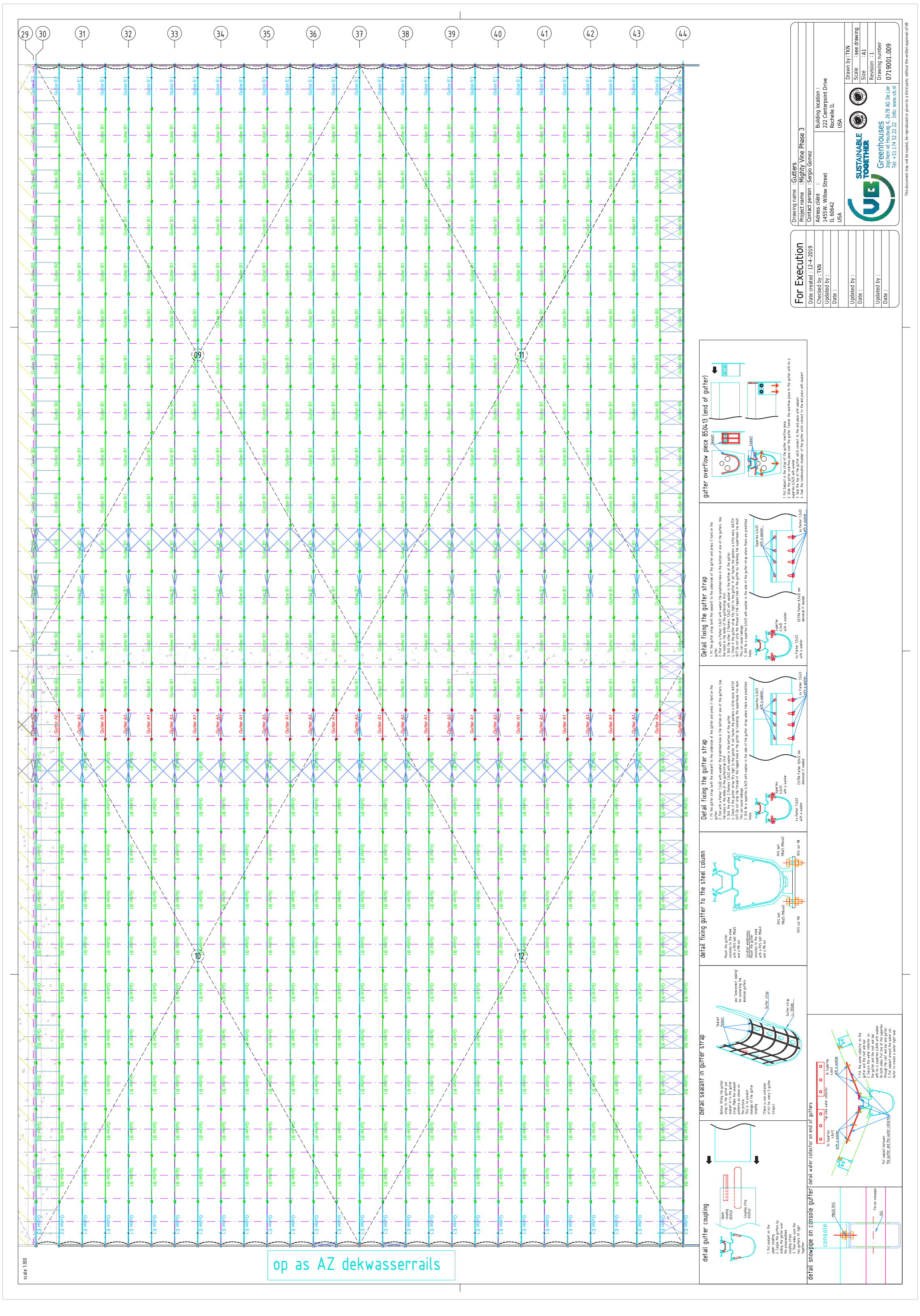
appendix 3-7

MightyVine phase 3 shoring lay-out by VB.



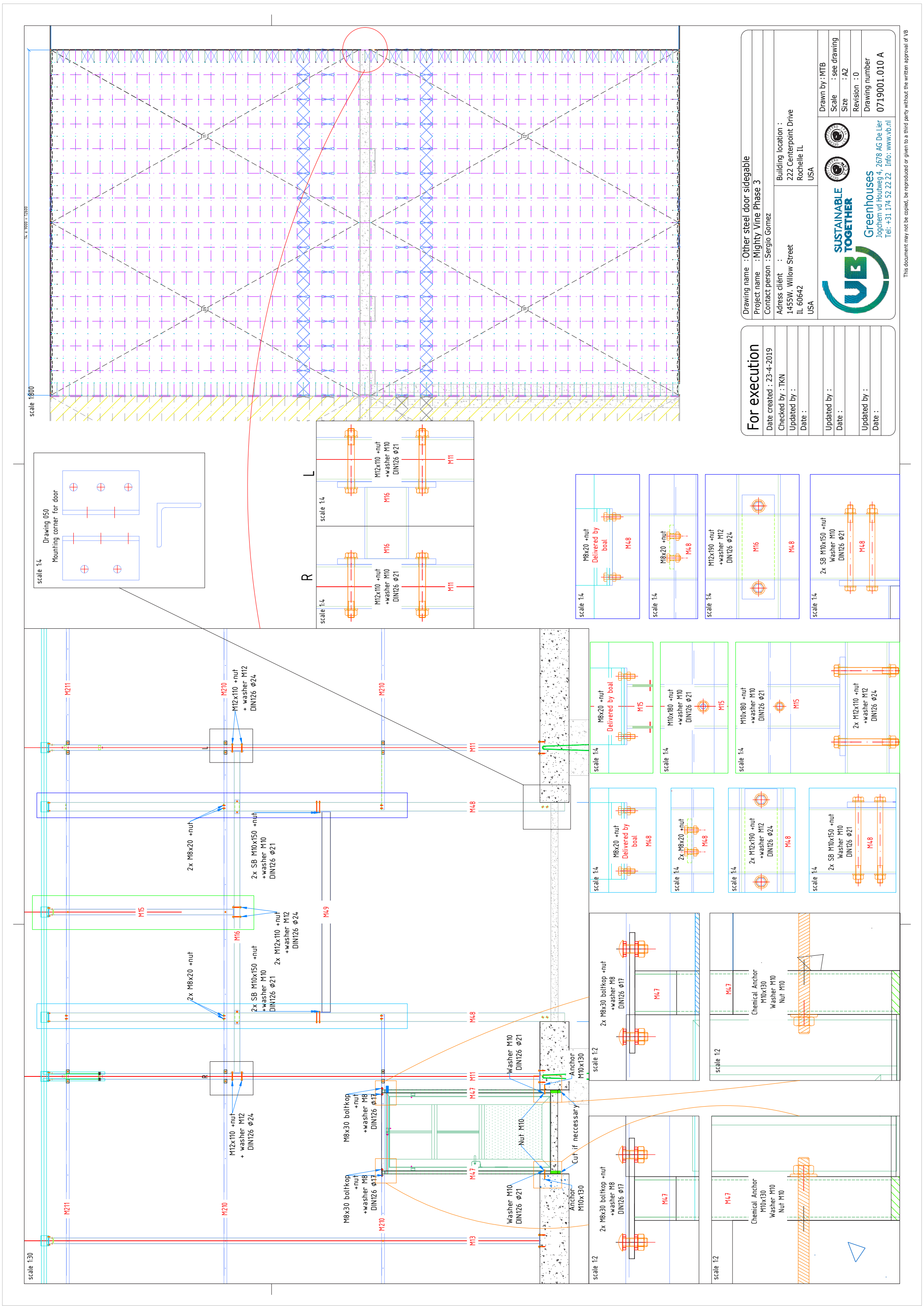
appendix 3-8

MightyVine phase 3 gutter lay-out by VB.



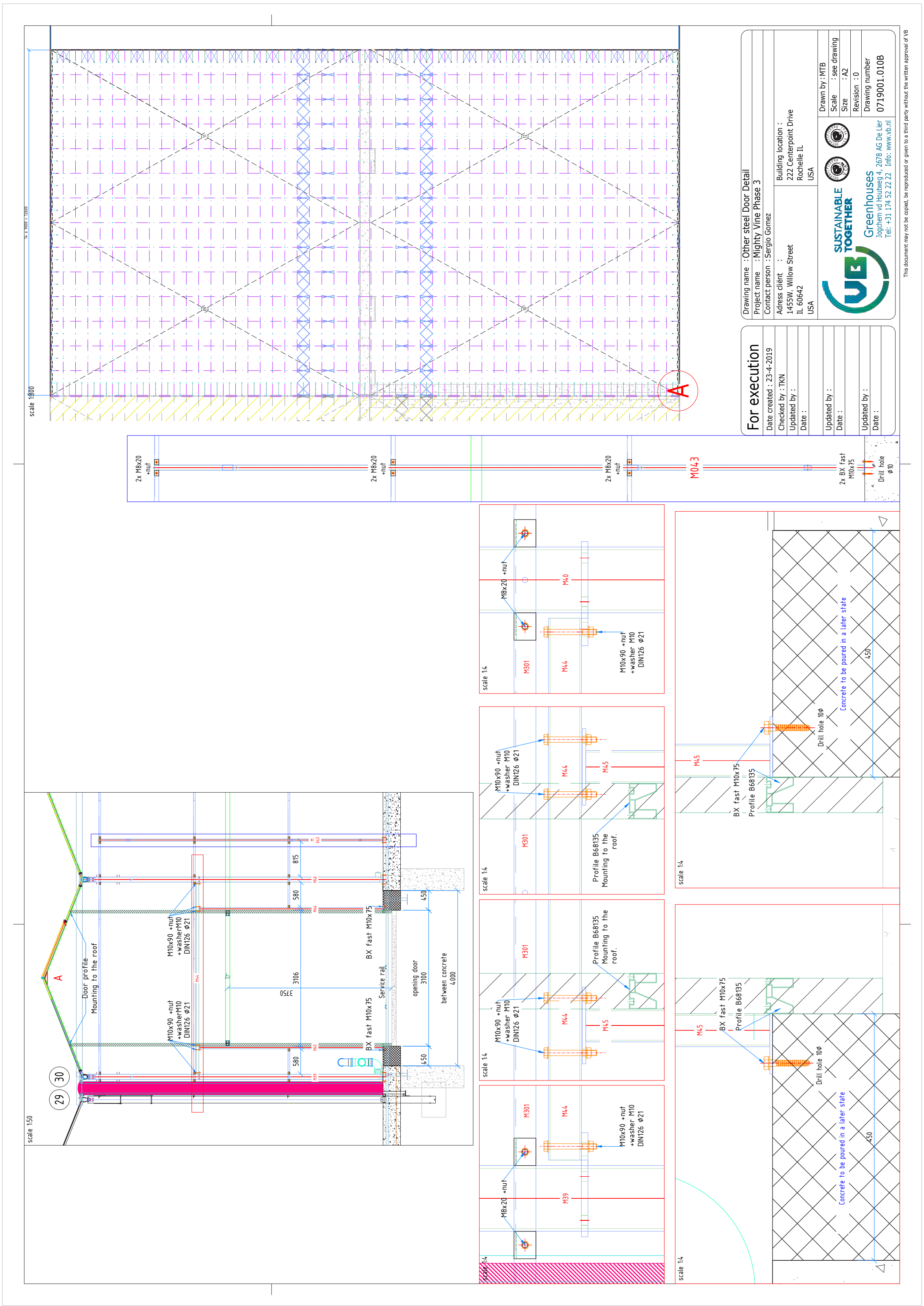
appendix 3-9

MightyVine phase 3 other steel by VB.



appendix 3-10

MightyVine phase 3 other steel by VB.



appendix 4

Tables of reusable components of MightyVine phase 3.

components

Wih the original AutoCAD drawings (latest revisions) and order lists for steel, aluminium, and glass, parts that went into MightyVines phase 3 were collected. In theory, all of these are available for reuse when the greenhouse is eventually demolished. Tables 999-999 present the parts and their dimensions, amounts, and structural properties. Product codes are included, which can be found in the drawings and order lists in appendix 999-999. Abbreviations in the column (Type) mean the following: RHS = rectangular hollow section, SHS = square hollow section, FL = flat plate, R = rod, U = U-profile. The abbreviation F in the column (Location) means field, and is followed by a field identifyer that can be retrieved in the appendix. Data for cross-section properties is derived from (Dlubal, n.d.).

table 1: steel columns (own, 2022)

Code	Element	Type	Steel	Location	l	b	t	Size	Number	Spare	A	V	G	I_y	I_z
[-]	[-]	[-]	[N/mm^2]	[-]	[mm]	[mm]	[mm]	[mm]	[#]	[#]	[cm^2]	[cm^3/m]	[kg/m]	[cm^4]	[cm^4]
M07	Column	RHS	S235	Midfield	160	60	4	6,383	588	-	16.50	1,650.00	13.00	500.00	106.00
M08	Column	RHS	S235	Midfield	160	60	4	6,383	116	4	16.50	1,650.00	13.00	500.00	106.00
M09	Column	RHS	S235	Sidewall	160	80	4	6,733	19	-	18.10	1,810.00	14.20	598.00	204.00
M10	Column	RHS	S235	Sidewall	160	80	4	6,733	21	-	18.10	1,810.00	14.20	598.00	204.00
M11	Column	RHS	S235	Sidewall	160	80	4	6,733	2	-	18.10	1,810.00	14.20	598.00	204.00
M12	Column	RHS	S235	Sidewall	160	80	4	6,733	8	-	18.10	1,810.00	14.20	598.00	204.00
M13	Column	RHS	S235	Sidewall	160	80	4	6,733	47	1	18.10	1,810.00	14.20	598.00	204.00
M14	Column	RHS	S235	Sidewall	160	80	4	6,733	4	-	18.10	1,810.00	14.20	598.00	204.00
M15	Column	RHS	S235	Door	160	80	4	2,543	1	-	18.10	1,810.00	14.20	598.00	204.00
M16	Door beam	RHS	S235	Door	160	80	4	4,420	1	-	18.10	1,810.00	14.20	598.00	204.00
M30	Drain column	RHS	S235	Endwall	200	120	5	6,733	23	-	30.70	3,070.00	24.10	1,685.00	762.00
M31	Drain column	RHS	S235	Endwall	200	120	5	6,733	2	-	30.70	3,070.00	24.10	1,685.00	762.00
M32	Drain column	RHS	S235	Endwall	200	120	5	6,733	2	-	30.70	3,070.00	24.10	1,685.00	762.00
M33	Drain column	RHS	S235	Endwall	200	120	5	6,733	1	-	30.70	3,070.00	24.10	1,685.00	762.00
M34	Drain column	RHS	S235	Endwall	200	120	5	6,733	1	-	30.70	3,070.00	24.10	1,685.00	762.00
M35	Drain column	RHS	S235	Endwall	200	120	5	6,733	22	-	30.70	3,070.00	24.10	1,685.00	762.00
M36	Drain column	RHS	S235	Endwall	200	120	5	6,733	2	-	30.70	3,070.00	24.10	1,685.00	762.00
M37	Drain column	RHS	S235	Endwall	200	120	5	6,733	2	-	30.70	3,070.00	24.10	1,685.00	762.00
M38	Drain column	RHS	S235	Endwall	200	120	5	6,733	1	-	30.70	3,070.00	24.10	1,685.00	762.00
M39	Drain column	RHS	S235	Endwall	200	120	5	6,733	1	-	30.70	3,070.00	24.10	1,685.00	762.00
M40	Drain column	RHS	S235	Endwall	200	120	5	6,733	1	-	30.70	3,070.00	24.10	1,685.00	762.00

table 2: steel trellises (own, 2022)

Code	Element	Type	Steel	Location	l	b	t	Size	Number	Spare	A	V	G	I_y	I_z
[-]	[-]	[-]	[N/mm^2]	[-]	[mm]	[mm]	[mm]	[mm]	[#]	[#]	[cm^2]	[cm^3/m]	[kg/m]	[cm^4]	[cm^4]
M1	Top girder	RHS	S275	F03-12	60	30	3	8,840	501	1	4.24	424.00	3.30	18.41	6.11
M1	Bottom girder	RHS	S275	F03-12	60	30	3	8,840	501	1	4.24	424.00	3.30	18.41	6.11
M1	Diagonal	SHS	S235	F03-12	25	25	2	594	501	1	1.77	177.00	1.40	1.53	1.53
M1	Endplate	FL	S235	F03-12	60	12	-	576	501	1	7.20	720.00	5.70	0.86	21.60
M1	Mid vertical	RHS	S235	F03-12	50	25	2	440	501	1	2.74	274.00	2.20	8.38	2.81
M2	Top girder	RHS	S275	F01-02, F13	60	30	3	8,840	152	2	4.24	424.00	3.30	18.41	6.11
M2	Bottom girder	RHS	S275	F01-02, F13	60	30	3	8,840	152	2	4.24	424.00	3.30	18.41	6.11
M2	Diagonal	SHS	S235	F01-02, F13	25	25	2	594	152	2	1.77	177.00	1.40	1.53	1.53
M2	Endplate	FL	S235	F01-02, F13	60	12	-	576	152	2	7.20	720.00	5.70	0.86	21.60
M2	Mid vertical	RHS	S235	F01-02, F13	50	25	2	440	152	2	2.74	274.00	2.20	8.38	2.81
M3	Top girder	RHS	S275	F14	60	30	3	8,840	50	-	4.24	424.00	3.30	18.41	6.11
M3	Bottom girder	RHS	S275	F14	60	30	3	8,840	50	-	4.24	424.00	3.30	18.41	6.11
M3	Diagonal	SHS	S235	F14	25	25	2	594	50	-	1.77	177.00	1.40	1.53	1.53
M3	Endplate	FL	S235	F14	60	12	-	576	50	-	7.20	720.00	5.70	0.86	21.60
M3	Mid vertical	RHS	S235	F14	50	25	2	440	50	-	2.74	274.00	2.20	8.38	2.81
M4	Filling plate	FL	S235	All fields	60	5	-	576	150	-	3.00	300.00	2.40	0.06	9.00
M5	Mid trellis post	RHS	S235	All fields	120	60	3	213	651	1	10.21	1,021.00	8.00	189.12	64.40

table 3: steel bracing (own, 2022)

Code	Element	Type	Steel	Location	l	b	t	Size	Number	Spare	A	V	G	I_y	I_z
[-]	[-]	[-]	[N/mm^2]	[-]	[mm]	[mm]	[mm]	[mm]	[#]	[#]	[cm^2]	[cm^3/m]	[kg/m]	[cm^4]	[cm^4]
M17	Cross brace	R	S235	Midfield	⌀10	-	-	5,000	226	2	0.79	78.50	0.60	0.05	0.05
M18	Cross brace	R	S235	Sidewall	⌀10	-	-	3,330	32	-	0.79	78.50	0.60	0.05	0.05
M19	Cross brace	R	S235	Endwall	⌀10	-	-	6,800	8	-	0.79	78.50	0.60	0.05	0.05
M20	Cross brace beam	RHS	S235	Sidewall	120	60	3	4,440	56	-	10.21	1,021.00	8.00	189.12	64.40
M21	Upper beam	SHS	S235	Sidewall	50	50	2	4,440	57	1	3.74	374.00	2.90	14.15	28.30
M22	Middle beam	SHS	S235	Sidewall	50	50	2	4,440	57	1	3.74	374.00	2.90	14.15	28.30
M23	Upper beam	SHS	S235	Endwall	50	50	2	2,170	8	-	3.74	374.00	2.90	14.15	28.30
M24	Middle beam	SHS	S235	Endwall	50	50	2	2,170	8	-	3.74	374.00	2.90	14.15	28.30
M25	Cross wind brace	R	S235	Deck	⌀8	-	-	6,030	110	2	0.50	50.30	0.40	0.02	0.02

table 4: steel sidewall gutter supports (own, 2022)

Code	Element	Type	Steel	Location	l	b	t	Size	Number	Spare	A	V	G	I_y	I_z
[-]	[-]	[-]	[N/mm^2]	[-]	[mm]	[mm]	[mm]	[mm]	[#]	[#]	[cm^2]	[cm^3/m]	[kg/m]	[cm^4]	[cm^4]
M26	Support	SHS	S235	Sidewall	50	50	2	4,453	51	-	3.74	374.00	2.90	14.15	28.30
M27	Support brace	R	S235	Sidewall	⌀10	-	-	4,600	108	2	0.79	78.50	0.60	0.05	0.05
M28	Support dilatation	RHS	S235	Sidewall	100	50	3	4,600	51	-	7.09	709.00	5.60	91.20	31.10

table 5: steel purlins (own, 2022)

Code	Element	Type	Steel	Location	l	b	t	Size	Number	Spare	A	V	G	I_y	I_z
[-]	[-]	[-]	[N/mm^2]	[-]	[mm]	[mm]	[mm]	[mm]	[#]	[#]	[cm^2]	[cm^3/m]	[kg/m]	[cm^4]	[cm^4]
M200	Purlin*	U	S235	Sidewall	80	40	2	4,496	41	-	2.97	297.00	2.30	26.60	4.78
M201	Purlin*	U	S235	Sidewall	80	40	2	4,426	49	-	2.97	297.00	2.30	26.60	4.78
M210	Purlin*	U	S235	Sidewall	80	40	2	4,496	99	1	2.97	297.00	2.30	26.60	4.78
M211	Purlin*	U	S235	Sidewall	80	40	2	4,426	49	-	2.97	297.00	2.30	26.60	4.78
M212	Corner purlin*	U	S235	Sidewall	80	40	2	4,663	2	-	2.97	297.00	2.30	26.60	4.78
M213	Corner purlin*	U	S235	Sidewall	80	40	2	4,663	2	-	2.97	297.00	2.30	26.60	4.78
M214	Corner purlin*	U	S235	Sidewall	80	40	2	4,628	1	-	2.97	297.00	2.30	26.60	4.78
M215	Corner purlin*	U	S235	Sidewall	80	40	2	4,628	1	-	2.97	297.00	2.30	26.60	4.78
M202	Corner purlin*	U	S235	Sidewall	80	40	2	4,663	3	1	2.97	297.00	2.30	26.60	4.78
M203	Corner purlin*	U	S235	Sidewall	80	40	2	4,663	3	1	2.97	297.00	2.30	26.60	4.78
M204	Corner purlin*	U	S235	Sidewall	80	40	2	4,628	1	-	2.97	297.00	2.30	26.60	4.78
M205	Corner purlin*	U	S235	Sidewall	80	40	2	4,628	1	-	2.97	297.00	2.30	26.60	4.78
M300	Purlin	U	S235	Endwall	100	40	3	9,150	72	-	5.10	510.00	4.00	74.48	7.52
M301	Purlin	U	S235	FW (F01)	100	40	3	10,385	4	1	5.10	510.00	4.00	74.48	7.52
M302	Purlin	U	S235	FW (F14)	100	40	3	8,070	3	-	5.10	510.00	4.00	74.48	7.52
M303	Purlin	U	S235	FW (F01)	100	40	3	10,190	4	1	5.10	510.00	4.00	74.48	7.52
M304	Purlin	U	S235	FW (F14)	100	40	3	8,265	3	-	5.10	510.00	4.00	74.48	7.52

table 6: aluminium gutters (own, 2022)

Code [-]	Product number [-]	Grid position (30-44) [-]	Grid position (A-AZ) [-]	Length [mm]	Number [#]
A1	GT50505	30-31	Z-AA	5,625	26
A2	GT50505	32-42	Z-AA	5,625	2
A3	GT50505	43	Z-AA	5,625	1
A4	GT50505	44	Z-AA	5,625	1
B1	GT50505	30-31	C-Y and AB-AX	9,000	578
B2	GT50505	32-42	C-Y and AB-AX	9,000	46
B3	GT50505	43	C-Y and AB-AX	9,000	23
B4	GT50505	44	C-Y and AB-AX	9,000	23
E1	GT50506-E	30-31	A-C and AX-AZ	8,848	52
E2	GT50506-E	32-42	A-C and AX-AZ	8,848	4
E3	GT50506-E	43	A-C and AX-AZ	8,848	2
E4	GT50506-E	44	A-C and AX-AZ	8,848	2

table 7: aluminium ridges (own, 2022)

Product number [-]	Length [mm]	Number [-]
NK50343/9000	9,000	703
NK50343/5300	5,300	30

table 8: deck panes (own, 2022)

Code [-]	Type [-]	Length [mm]	Width [mm]	Number [#]	Total area [m^2]
A	70% Haze and 2x AR treatment	2,382	1,120	6,797	18,134
B	70% Haze and 2x AR treatment	2,382	558	1,028	1,367
C	70% Haze and 2x AR treatment	1,400	549	463	356
D	70% Haze and 2x AR treatment	995	558	463	257
E	70% Haze and 2x AR treatment	1,400	1,112	4,113	6,403
F	70% Haze and 2x AR treatment	995	1,120	4,113	4,583
G	70% Haze and 2x AR treatment	2,382	250	117	70

table9: gable panes (own, 2022)

Code [-]	Type [-]	Length [mm]	Width [mm]	Number [#]	Total area [m2]
A	4mm single tempered glass 89%	2,134	735	856	1,343
B	4mm single tempered glass 89%	2,134	360	80	61
C	4mm single tempered glass 89%	320	735	249	59
D	4mm single tempered glass 89%	320	360	44	5
E	4mm single tempered glass 89%	840	314	110	29
F	4mm single tempered glass 89%	1,614	735	55	65
G	4mm single tempered glass 89%	320	167	3	0
H	4mm single tempered glass 89%	2,134	167	7	2

table 10: aluminium rods (own, 2022)

Product number [-]	Location [-]	Length [mm]	Number [#]
GR50496	Facade	6,790	225
GR50496	Facade	6,790	102
GR50496	Facade	850	106
GR50264	Facade	6,674	30
GR50264	Facade	7,189	58
GR50264	Facade	7,545	58
GR50264	Facade	6,569	30
GR50264	Facade	7,189	58
GR50264	Facade	7,545	58
DR51101/2382	Deck	4,500	12,250
DR50444/2382R	Deck (right)	4,500	10
DR50444/2382	Deck (left)	4,500	10
DH50282/2382-50-R	Deck edge (right)	4,500	59
DH50282/2382-50-L	Deck edge (left)	4,500	59

appendix 5

appendix 5

Plan optimizations of module configurations from 1 to 4 trellises long and 1 to 4 bays deep.

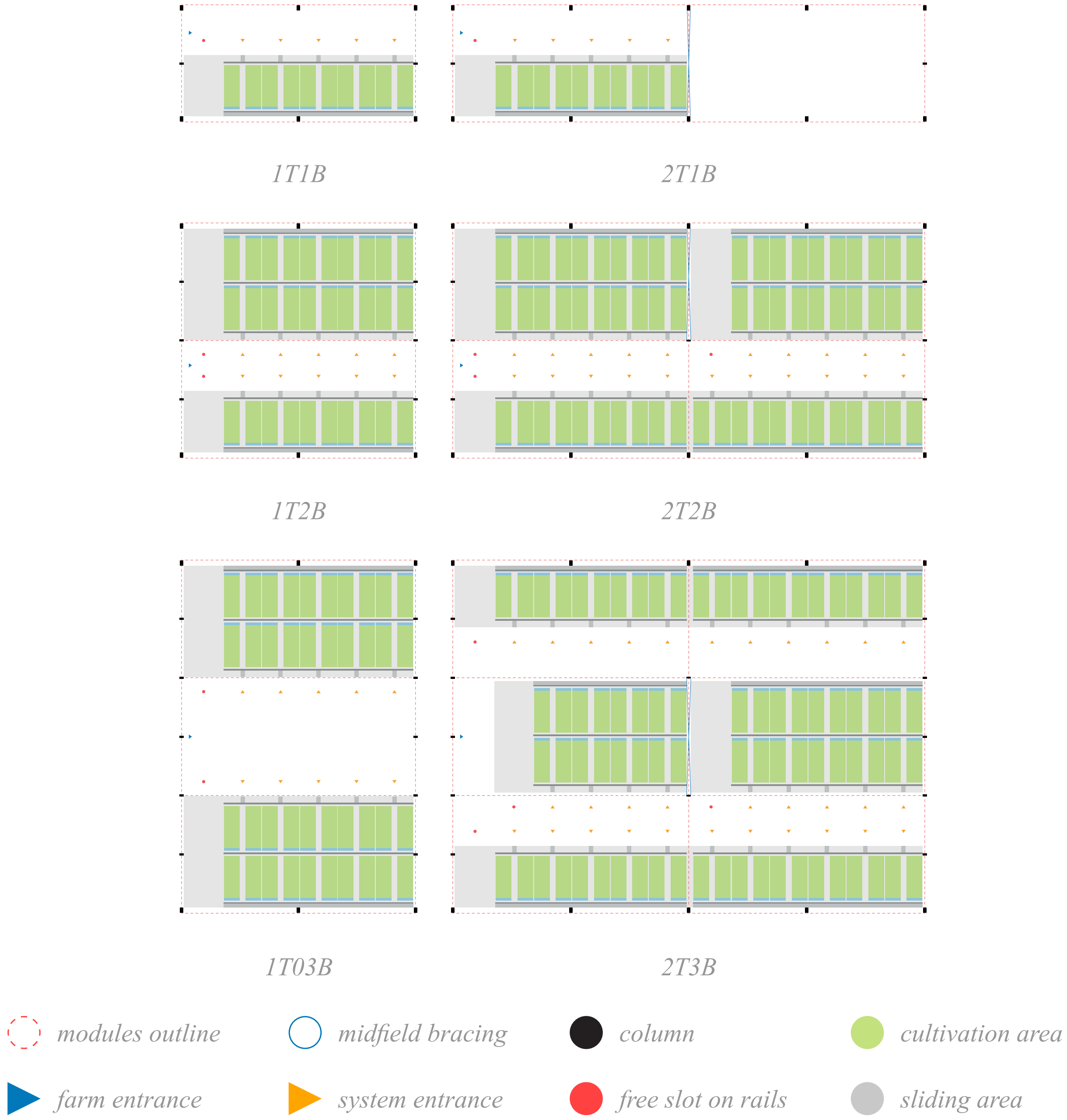
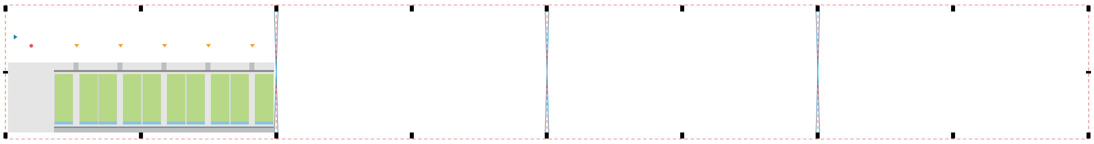


figure 1: plans of module configurations with one and two trellises and one to three bays (own, 2023)

figure 2: plans of module configurations with three trellises and one to three bays (own, 2023)



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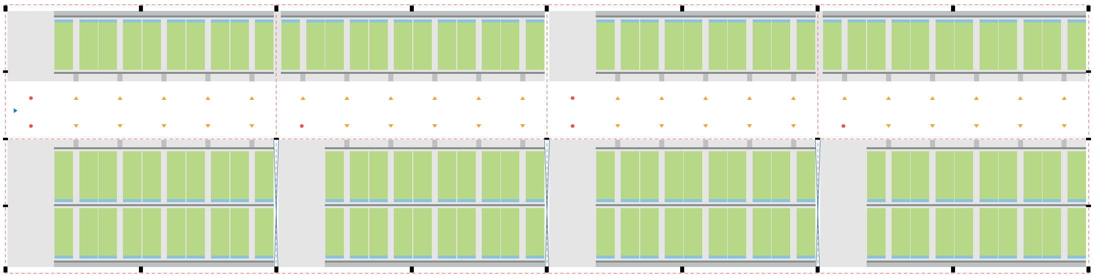

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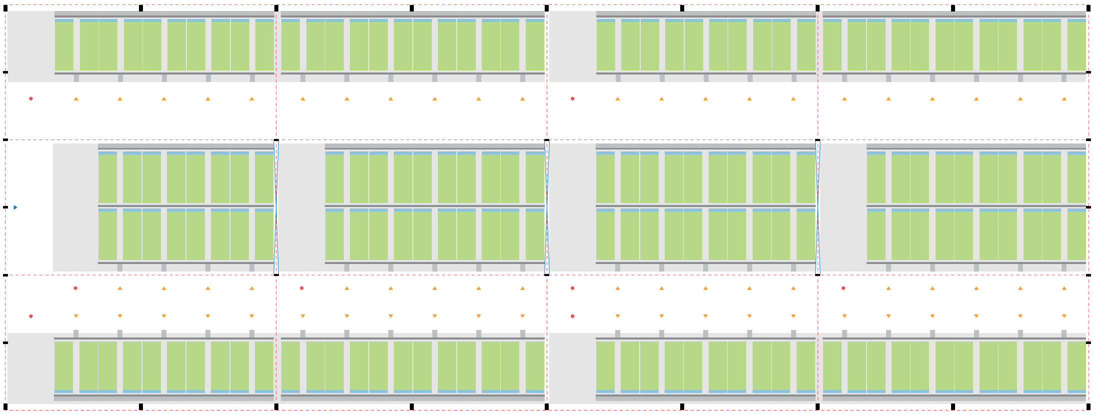


4T3B

◌ modules outline
○ midfield bracing
● column
🟢 cultivation area
▶ farm entrance
▶ system entrance
🔴 free slot on rails
⚪ sliding area

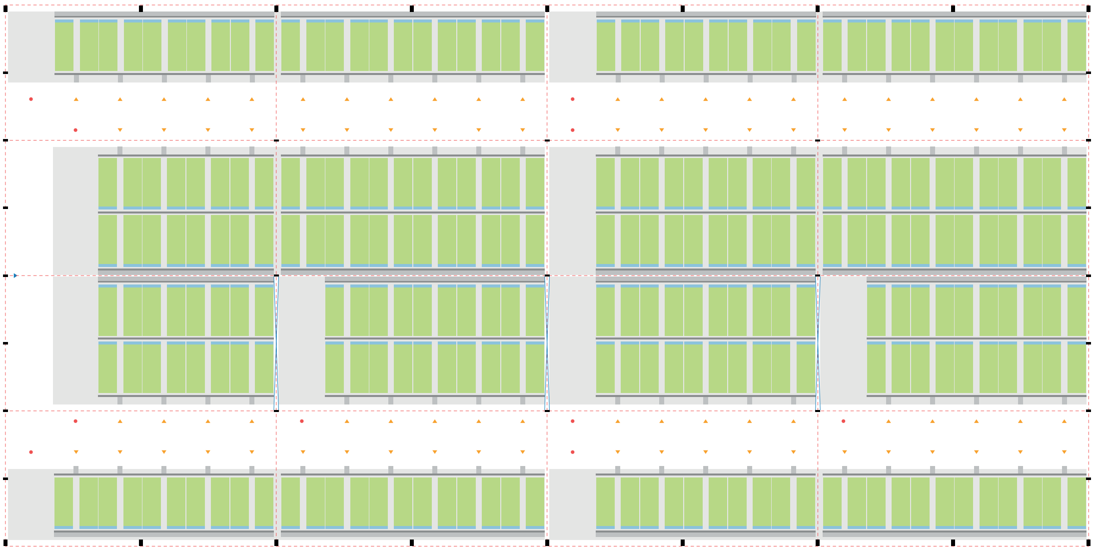
figure 3: plans of module configurations with four trellises and one to three bays (own, 2023)

1T4B

2T4B

3T4B

figure 4: plans of module configurations with one to three trellises and four bays (own, 2023)



4T4B

figure 5: plan of a module configuration with four trellises and four bays (own, 2023)

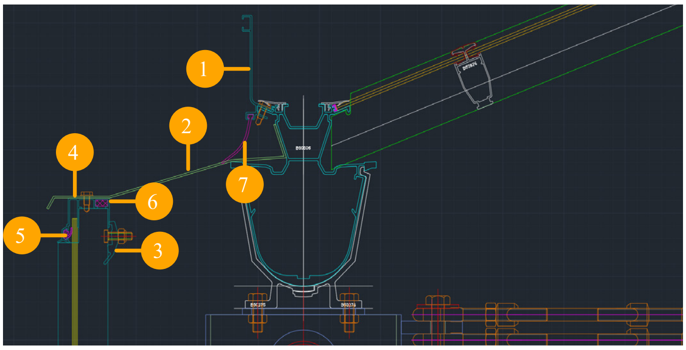
appendix 6

appendix 6a

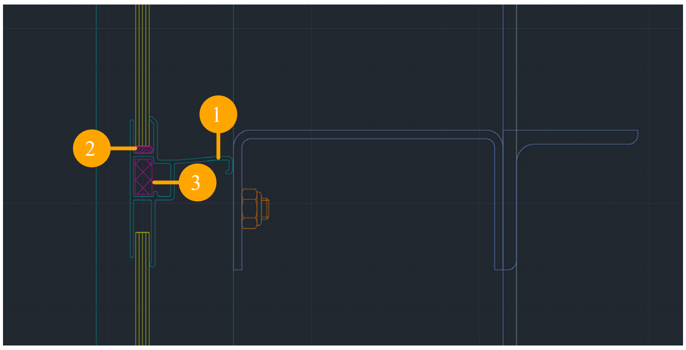
Aluminium profiles, rubbers, and PVC strips in gable details.

gable details

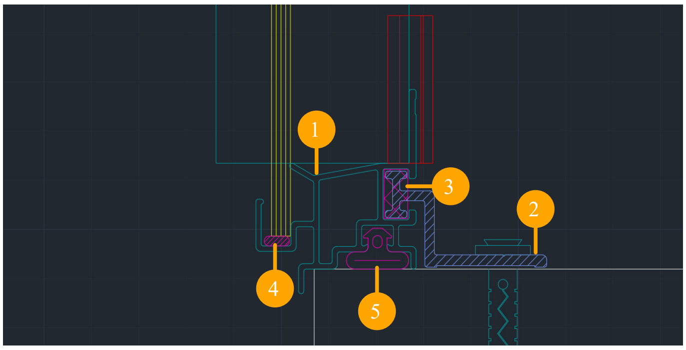
The names and/or functions of the components in the gable details are not relevant, this appendix is added for the purpose of showing that the author realizes that there are many small components incorporated into the main construction that also contribute to the carbon footprint. In *figure 1* the gable details of MightyVine phase 3 as drawn by the consortium that designed and constructed it are presenten. In the details, the various aluminium profiles, rubbers, and strips are designated by numbers, which are named in the tables next to the details and of which the material and cross-sectional areas are given. In these details, the cross-sectional area of the vertical rod is not drawn, it is only visible in elevation. The crosssectional area of a vertical rod is 206.73.... mm^2, and it is covered by a PVC strip with a cross-sectional area of 53.47.... mm^2.



No. [-]	Code [-]	Material [-]	Crossectional area [mm^2]
1		Aluminium	189.640
2		Aluminium	343.943
3		Aluminium	143.946
4		Aluminium	162.555
5		Rubber	32.651
6		Rubber	50.000
7		Rubber	83.913



No. [-]	Code [-]	Material [-]	Crossectional area [mm^2]
1		Aluminium	133.136
2		Rubber	9.712
3		Rubber	50.000



No. [-]	Code [-]	Material [-]	Crossectional area [mm^2]
1		Aluminium	176.198
2		Aluminium	117.264
3		Rubber	50.000
4		Rubber	9.712
5		Rubber	63.549

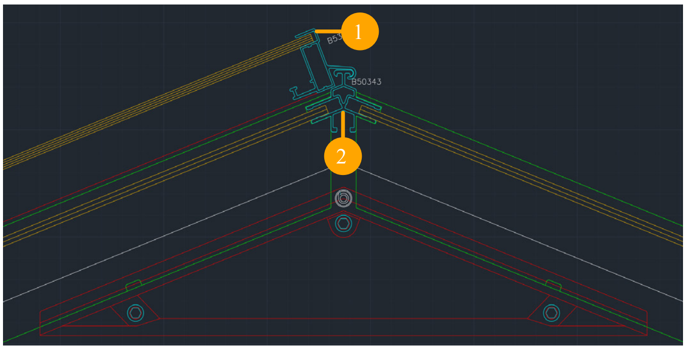
figure 1: MightyVine phase 3 gable construction details (VB, 2019)

appendix 6b

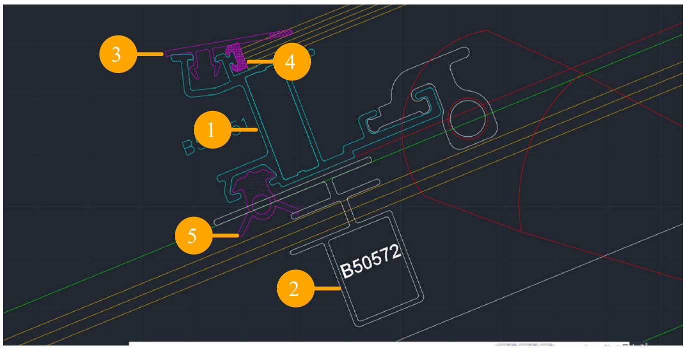
Aluminium profiles, rubbers, and PVC strips in deck details.

deck details

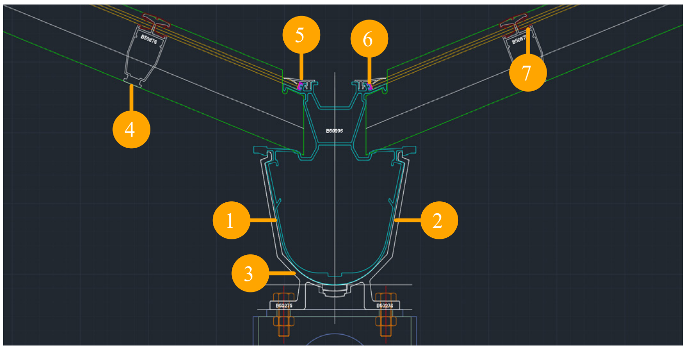
The names and/or functions of the components in the gable details are not relevant, this appendix is added for the purpose of showing that the author realizes that there are many small components incorporated into the main construction that also contribute to the carbon footprint. In *figure 2* the deck details of MightyVine phase 3 as drawn by the consortium that designed and constructed it are presenten. In the details, the various aluminium profiles, rubbers, and strips are designated by numbers, which are named in the tables next to the details and of which the material and cross-sectional areas are given.



No. [-]	Code [-]	Material [-]	Crossectional area [mm^2]
1	B5396	Aluminium	117.315
2	B50343	Aluminium	164.190



No. [-]	Code [-]	Material [-]	Crossectional area [mm^2]
1	B50451	Aluminium	175.976
2	B50572	Aluminium	127.378
3		PVC	32.977
4		Rubber	10.711
5		Rubber	45.222



No. [-]	Code [-]	Material [-]	Crossectional area [mm^2]
1	B50276	Aluminium	695.454
2	B50276	Aluminium	690.492
3	B50876	Aluminium	1,271.882
4		Aluminium	232.863
5		PVC	30.618
6		Rubber	10.711
7		PVC	25.389

figure 2: MightyVine phase 3 deck construction details (VB, 2019)

appendix 7

appendix 7a

Carbon footprint of a trellis-link corner, a bay-link corner, and an endwall module.

table 1: carbon footprint of corner and endwall modules (own, 2023)

				Bay-link corner			Trellis-link corner			Endwall		
Group	Material	Component	R/N	Volume	Weight	Footprint	Volume	Weight	Footprint	Volume	Weight	Footprint
[-]	[-]	[-]	[-]	[m^3]	[kg]	[$kgCO_{2\text{-eq}}$]	[m^3]	[kg]	[$kgCO_{2\text{-eq}}$]	[m^3]	[kg]	[$kgCO_{2\text{-eq}}$]
Foundation	Concrete	Endwall pile	N	1.28118	3,074.8	3,144.7	1.28118	3,074.8	3,144.7	1.13883	2,733.2	2,795.3
	Concrete	Sidewall pile	N	0.28502	684.1	699.6	0.28502	684.1	699.6	-	-	-
	Concrete	Midfield pile	N	0.06258	150.2	153.6	0.06258	150.2	153.6	0.12517	300.4	307.2
	Concrete	Facade beam	N	1.30176	3,124.2	3,195.2	1.30176	3,124.2	3,195.2	0.86400	2,073.6	2,120.7
	Stainless steel	Midfield column	N	0.00040	3.1	6.0	0.00040	3.1	6.0	0.00080	6.3	12.0
	Galvanized steel	Column foot plate	N	0.00002	0.2	0.3	0.00002	0.2	0.3	0.00005	0.4	0.7
Structure	Galvanized steel	Endwall column	R	0.05210	408.9	736.5	0.05210	408.9	736.5	0.04168	327.2	589.2
	Galvanized steel	Sidewall column	R	0.01871	146.9	264.6	0.01871	146.9	264.6	-	-	-
	Galvanized steel	Midfield column	R	0.00270	21.2	38.2	0.00270	21.2	38.2	0.00541	42.5	76.5
	Galvanized steel	Column foot plate	R	0.00060	4.7	8.5	0.00060	4.7	8.5	0.00030	2.4	4.2
	Galvanized steel	Endwall purlin	R	0.01316	103.3	186.1	0.01316	103.3	186.1	0.01295	101.6	183.0
	Galvanized steel	Endwall purlin corner	R	0.00018	1.4	2.6	0.00018	1.4	2.6	0.00018	1.4	2.6
	Galvanized steel	Sidewall purlin	R	0.00509	39.9	71.9	0.00509	39.9	71.9	-	-	-
	Galvanized steel	Sidewall purlin corner	R	0.00014	1.1	2.0	0.00014	1.1	2.0	-	-	-
	Galvanized steel	Trellis end plate	R	0.00041	3.3	5.9	0.00041	3.3	5.9	0.00041	3.3	5.9
	Galvanized steel	Mid vertical foot plate	R	0.00004	0.3	0.5	0.00004	0.3	0.5	0.00004	0.3	0.5
	Galvanized steel	Trellis girders	R	0.00375	29.4	53.0	0.00375	29.4	53.0	0.00375	29.4	53.0
	Galvanized steel	Trellis gutter plate	R	0.00008	0.6	1.1	0.00008	0.6	1.1	0.00007	0.5	0.9
	Galvanized steel	Endwall gutter plate	R	0.00075	5.9	10.6	0.00075	5.9	10.6	0.00060	4.7	8.5
	Galvanized steel	Sidewall gutter plate	R	0.00007	0.5	0.9	0.00007	0.5	0.9	-	-	-
	Galvanized steel	Mid trellis post	R	0.00011	0.8	1.5	0.00011	0.8	1.5	0.00011	0.8	1.5
	Galvanized steel	Trellis mid vertical	R	0.00006	0.5	0.9	0.00006	0.5	0.9	0.00006	0.5	0.9
	Galvanized steel	Trellis diagonal	R	0.00109	8.6	15.5	0.00109	8.6	15.5	0.00109	8.6	15.5
	Galvanized steel	Gutter support beam	R	0.00170	13.3	24.0	0.00170	13.3	24.0	-	-	-
	Stainless steel	Gutter support bracing	R	0.00075	5.9	11.2	0.00075	5.9	11.2	-	-	-
	Galvanized steel	Gutter. sup. bracing strip	R	0.00004	0.4	0.6	0.00004	0.4	0.6	-	-	-
	Galvanized steel	Gutter sup. gutter plate	R	0.00003	0.2	0.4	0.00003	0.2	0.4	-	-	-
	Aluminium	Gutter sup. gut. console	R	0.00007	0.2	3.1	0.00007	0.2	3.1	-	-	-
Facade	Aluminium	Endwall vertical aluminium	R	0.02927	79.0	1,314.8	0.02648	71.5	1,189.6	0.01533	41.4	688.7
	PVC	Endwall vertical PVC	N	0.00757	10.1	21.9	0.00685	9.1	19.8	0.00397	5.3	11.5
	Aluminium	Sidewall vertical aluminium	R	0.01828	49.4	821.3	0.01828	49.4	821.3	-	-	-
	PVC	Sidewall vertical PVC	N	0.00473	6.3	13.7	0.00473	6.3	13.7	-	-	-
	Aluminium	Endwall horizontal aluminium	R	0.00624	16.8	280.2	0.00624	16.8	280.2	0.00624	16.8	280.2
	Rubber	Endwall horizontal rubber	N	0.00272	4.1	14.1	0.00272	4.1	14.1	0.00272	4.1	14.1
	Aluminium	Sidewall horizontal aluminium	R	0.00690	18.6	309.9	0.00690	18.6	309.9	-	-	-
	Rubber	Sidewall horizontal rubber	N	0.00211	3.2	10.9	0.00211	3.2	10.9	-	-	-
	Glass	Panes	R	0.35949	898.7	608.8	0.36074	901.8	610.9	0.25240	631.0	427.4
	Aluminium	Corner cladding	R	0.00904	24.4	406.0	0.00904	24.4	406.0	-	-	-
Deck	Aluminium	Gutter console	R	0.00135	3.6	60.6	0.00135	3.6	60.6	0.00108	2.9	48.6
	Aluminium	Gutter	R	0.01539	41.6	691.4	0.01539	41.6	691.4	0.01231	33.2	553.1
	Rubber	Gutter rubber	N	0.00021	0.3	1.1	0.00021	0.3	1.1	0.00021	0.3	1.1
	PVC	Gutter PVC	N	0.00059	0.8	1.7	0.00059	0.8	1.7	0.00059	0.8	1.7
	Aluminium	Deck rods	R	0.02104	56.8	945.4	0.02104	56.8	945.4	0.02104	56.8	945.4
	PVC	Deck rods PVC	N	0.00229	3.1	6.6	0.00229	3.1	6.6	0.00229	3.1	6.6
	Aluminium	Ridge	R	0.00079	2.1	35.7	0.00079	2.1	35.7	0.00079	2.1	35.7
	Aluminium	Window frame	R	0.00367	9.9	164.9	0.00367	9.9	164.9	0.00367	9.9	164.9
	Rubber	Window frame rubber	N	0.00019	0.3	1.0	0.00019	0.3	1.0	0.00019	0.3	1.0
	PVC	Window frame PVC	N	0.00036	0.5	1.0	0.00036	0.5	1.0	0.00036	0.5	1.0
	Glass	Panes	R	0.15582	389.5	263.9	0.15582	389.5	263.9	0.15582	389.5	263.9
Total		Total			**9,453**	**14,614**		**9,448**	**14,489**		**6,835**	**9,623**
		New			7,065	7,272		7,064	7,269		5,128	5,273
		New %			75%	50%		75%	50%		75%	55%
		Reuse			2,388.0	7,343		2,383.6	7,220		1,706.9	4,350
		Reuse %			25%	50%		25%	50%		25%	45%

appendix 7b

Carbon footprint of a half-pane sidewall, a transition sidewall, and a full-pane sidewall module.

table 2: carbon footprint of sidewall modules (own, 2023)

				Half-pane sidewall			Transition sidewall			Full-pane sidewall		
Group	Material	Component	R/N	Volume	Weight	Footprint	Volume	Weight	Footprint	Volume	Weight	Footprint
[-]	[-]	[-]	[-]	[m^3]	[kg]	[$kgCO_{2-eq}$]	[m^3]	[kg]	[$kgCO_{2-eq}$]	[m^3]	[kg]	[$kgCO_{2-eq}$]
Foundation	Concrete	Endwall pile	N	-	-	-	-	-	-	-	-	-
	Concrete	Sidewall pile	N	0.57005	1,368.1	1,399.2	0.57005	1,368.1	1,399.2	0.57005	1,368.1	1,399.2
	Concrete	Midfield pile	N	0.12517	300.4	307.2	0.12517	300.4	307.2	0.12517	300.4	307.2
	Concrete	Facade beam	N	0.43200	1,036.8	1,060.4	0.43200	1,036.8	1,060.4	0.43200	1,036.8	1,060.4
	Stainless steel	Midfield column	N	0.00080	6.3	12.0	0.00080	6.3	12.0	0.00080	6.3	12.0
	Galvanized steel	Column foot plate	N	0.00005	0.4	0.7	0.00005	0.4	0.7	0.00005	0.4	0.7
Structure	Galvanized steel	Endwall column	R	-	-	-	-	-	-	-	-	-
	Galvanized steel	Sidewall column	R	0.02495	195.9	352.8	0.02495	195.9	352.8	0.02495	195.9	352.8
	Galvanized steel	Midfield column	R	0.00541	42.5	76.5	0.00541	42.5	76.5	0.00541	42.5	76.5
	Galvanized steel	Column foot plate	R	0.00030	2.4	4.2	0.00030	2.4	4.2	0.00030	2.4	4.2
	Galvanized steel	Endwall purlin	R	-	-	-	-	-	-	-	-	-
	Galvanized steel	Endwall purlin corner	R	-	-	-	-	-	-	-	-	-
	Galvanized steel	Sidewall purlin	R	0.00512	40.2	72.4	0.00512	40.2	72.4	0.00512	40.2	72.4
	Galvanized steel	Sidewall purlin corner	R	0.00009	0.7	1.3	0.00009	0.7	1.3	0.00009	0.7	1.3
	Galvanized steel	Trellis end plate	R	0.00083	6.5	11.7	0.00083	6.5	11.7	0.00083	6.5	11.7
	Galvanized steel	Mid vertical foot plate	R	0.00008	0.6	1.1	0.00008	0.6	1.1	0.00008	0.6	1.1
	Galvanized steel	Trellis girders	R	0.00749	58.8	105.9	0.00749	58.8	105.9	0.00749	58.8	105.9
	Galvanized steel	Trellis gutter plate	R	0.00016	1.3	2.3	0.00016	1.3	2.3	0.00016	1.3	2.3
	Galvanized steel	Endwall gutter plate	R	-	-	-	-	-	-	-	-	-
	Galvanized steel	Sidewall gutter plate	R	0.00007	0.5	0.9	0.00007	0.5	0.9	0.00007	0.5	0.9
	Galvanized steel	Mid trellis post	R	0.00021	1.7	3.0	0.00021	1.7	3.0	0.00021	1.7	3.0
	Galvanized steel	Trellis mid vertical	R	0.00012	1.0	1.8	0.00012	1.0	1.8	0.00012	1.0	1.8
	Galvanized steel	Trellis diagonal	R	0.00219	17.2	30.9	0.00219	17.2	30.9	0.00219	17.2	30.9
	Galvanized steel	Gutter support beam	R	0.00170	13.3	24.0	0.00170	13.3	24.0	0.00170	13.3	24.0
	Stainless steel	Gutter support bracing	R	0.00075	5.9	11.2	0.00075	5.9	11.2	0.00075	5.9	11.2
	Galvanized steel	Gutter. sup. bracing strip	R	0.00004	0.4	0.6	0.00004	0.4	0.6	0.00004	0.4	0.6
	Galvanized steel	Gutter sup. gutter plate	R	0.00003	0.2	0.4	0.00003	0.2	0.4	0.00003	0.2	0.4
	Aluminium	Gutter sup. gut. console	R	0.00007	0.2	3.1	0.00007	0.2	3.1	0.00007	0.2	3.1
Facade	Aluminium	Endwall vertical aluminium	R	-	-	-	-	-	-	-	-	-
	PVC	Endwall vertical PVC	N	-	-	-	-	-	-	-	-	-
	Aluminium	Sidewall vertical aluminium	R	0.01828	49.4	821.3	0.01406	38.0	631.8	0.00984	26.6	442.2
	PVC	Sidewall vertical PVC	N	0.00473	6.3	13.7	0.00364	4.8	10.5	0.00255	3.4	7.4
	Aluminium	Endwall horizontal aluminium	R	-	-	-	-	-	-	-	-	-
	Rubber	Endwall horizontal rubber	N	-	-	-	-	-	-	-	-	-
	Aluminium	Sidewall horizontal aluminium	R	0.00690	18.6	309.9	0.00690	18.6	309.9	0.00690	18.6	309.9
	Rubber	Sidewall horizontal rubber	N	0.00211	3.2	10.9	0.00211	3.2	10.9	0.00211	3.2	10.9
	Glass	Panes	R	0.11342	283.6	192.1	0.11519	288.0	195.1	0.11696	292.4	198.1
	Aluminium	Corner cladding	R	-	-	-	-	-	-	-	-	-
Deck	Aluminium	Gutter console	R	0.00063	1.7	28.3	0.00063	1.7	28.3	0.00063	1.7	28.3
	Aluminium	Gutter	R	0.01431	38.6	642.9	0.01431	38.6	642.9	0.01431	38.6	642.9
	Rubber	Gutter rubber	N	0.00019	0.3	1.0	0.00019	0.3	1.0	0.00019	0.3	1.0
	PVC	Gutter PVC	N	0.00055	0.7	1.6	0.00055	0.7	1.6	0.00055	0.7	1.6
	Aluminium	Deck rods	R	0.01772	47.8	796.1	0.01772	47.8	796.1	0.01772	47.8	796.1
	PVC	Deck rods PVC	N	0.00193	2.6	5.6	0.00193	2.6	5.6	0.00193	2.6	5.6
	Aluminium	Ridge	R	0.00074	2.0	33.2	0.00074	2.0	33.2	0.00074	2.0	33.2
	Aluminium	Window frame	R	0.00367	9.9	164.9	0.00319	8.6	143.3	0.00271	7.3	121.7
	Rubber	Window frame rubber	N	0.00019	0.3	1.0	0.00019	0.3	1.0	0.00019	0.3	1.0
	PVC	Window frame PVC	N	0.00036	0.5	1.0	0.00030	0.4	0.9	0.00025	0.3	0.7
	Glass	Panes	R	0.15265	381.6	258.5	0.15317	382.9	259.4	0.15405	385.1	260.9
Total		Total			**3,948**	**6,766**		**3,940**	**6,555**		**3,932**	**6,345**
		New			2,726	2,814		2,724	2,811		2,723	2,808
		New %			69%	42%		69%	43%		69%	44%
		Reuse			1,222.3	3,951		1,215.4	3,744		1,209.3	3,537
		Reuse %			31%	58%		31%	57%		31%	56%

appendix 7c

Carbon footprint of a half-pane midfield, a transition midfield, and a full-pane midfield module.

table 3: carbon footprint of midfield modules (own, 2023)

				Half-pane midfield			Transition midfield			Full-pane midfield		
Group	Material	Component	R/N	Volume	Weight	Footprint	Volume	Weight	Footprint	Volume	Weight	Footprint
[-]	[-]	[-]	[-]	$[m^3]$	[kg]	$[kgCO_{2\text{-}eq}]$	$[m^3]$	[kg]	$[kgCO_{2\text{-}eq}]$	$[m^3]$	[kg]	$[kgCO_{2\text{-}eq}]$
Foundation	Concrete	Endwall pile	N	-	-	-	-	-	-	-	-	-
	Concrete	Sidewall pile	N	-	-	-	-	-	-	-	-	-
	Concrete	Midfield pile	N	0.25034	600.8	614.5	0.25034	600.8	614.5	0.25034	600.8	614.5
	Concrete	Facade beam	N	-	-	-	-	-	-	-	-	-
	Stainless steel	Midfield column	N	0.00161	12.6	24.1	0.00161	12.6	24.1	0.00161	12.6	24.1
	Galvanized steel	Column foot plate	N	0.00010	0.8	1.4	0.00010	0.8	1.4	0.00010	0.8	1.4
Structure	Galvanized steel	Endwall column	R	-	-	-	-	-	-	-	-	-
	Galvanized steel	Sidewall column	R	-	-	-	-	-	-	-	-	-
	Galvanized steel	Midfield column	R	0.01082	84.9	152.9	0.01082	84.9	152.9	0.01082	84.9	152.9
	Galvanized steel	Column foot plate	R	-	-	-	-	-	-	-	-	-
	Galvanized steel	Endwall purlin	R	-	-	-	-	-	-	-	-	-
	Galvanized steel	Endwall purlin corner	R	-	-	-	-	-	-	-	-	-
	Galvanized steel	Sidewall purlin	R	-	-	-	-	-	-	-	-	-
	Galvanized steel	Sidewall purlin corner	R	-	-	-	-	-	-	-	-	-
	Galvanized steel	Trellis end plate	R	0.00083	6.5	11.7	0.00083	6.5	11.7	0.00083	6.5	11.7
	Galvanized steel	Mid vertical foot plate	R	0.00008	0.6	1.1	0.00008	0.6	1.1	0.00008	0.6	1.1
	Galvanized steel	Trellis girders	R	0.00749	58.8	105.9	0.00749	58.8	105.9	0.00749	58.8	105.9
	Galvanized steel	Trellis gutter plate	R	0.00013	1.0	1.8	0.00013	1.0	1.8	0.00013	1.0	1.8
	Galvanized steel	Endwall gutter plate	R	-	-	-	-	-	-	-	-	-
	Galvanized steel	Sidewall gutter plate	R	-	-	-	-	-	-	-	-	-
	Galvanized steel	Mid trellis post	R	0.00021	1.7	3.0	0.00021	1.7	3.0	0.00021	1.7	3.0
	Galvanized steel	Trellis mid vertical	R	0.00012	1.0	1.8	0.00012	1.0	1.8	0.00012	1.0	1.8
	Galvanized steel	Trellis diagonal	R	0.00219	17.2	30.9	0.00219	17.2	30.9	0.00219	17.2	30.9
	Galvanized steel	Gutter support beam	R	-	-	-	-	-	-	-	-	-
	Stainless steel	Gutter support bracing	R	-	-	-	-	-	-	-	-	-
	Galvanized steel	Gutter. sup. bracing strip	R	-	-	-	-	-	-	-	-	-
	Galvanized steel	Gutter sup. gutter plate	R	-	-	-	-	-	-	-	-	-
	Aluminium	Gutter sup. gut. console	R	-	-	-	-	-	-	-	-	-
Facade	Aluminium	Endwall vertical aluminium	R	-	-	-	-	-	-	-	-	-
	PVC	Endwall vertical PVC	N	-	-	-	-	-	-	-	-	-
	Aluminium	Sidewall vertical aluminium	R	-	-	-	-	-	-	-	-	-
	PVC	Sidewall vertical PVC	N	-	-	-	-	-	-	-	-	-
	Aluminium	Endwall horizontal aluminium	R	-	-	-	-	-	-	-	-	-
	Rubber	Endwall horizontal rubber	N	-	-	-	-	-	-	-	-	-
	Aluminium	Sidewall horizontal aluminium	R	-	-	-	-	-	-	-	-	-
	Rubber	Sidewall horizontal rubber	N	-	-	-	-	-	-	-	-	-
	Glass	Panes	R	-	-	-	-	-	-	-	-	-
	Aluminium	Corner cladding	R	-	-	-	-	-	-	-	-	-
Deck	Aluminium	Gutter console	R	0.00036	1.0	16.2	0.00036	1.0	16.2	0.00036	1.0	16.2
	Aluminium	Gutter	R	0.01145	30.9	514.3	0.01145	30.9	514.3	0.01145	30.9	514.3
	Rubber	Gutter rubber	N	0.00019	0.3	1.0	0.00019	0.3	1.0	0.00019	0.3	1.0
	PVC	Gutter PVC	N	0.00055	0.7	1.6	0.00055	0.7	1.6	0.00055	0.7	1.6
	Aluminium	Deck rods	R	0.01772	47.8	796.1	0.01772	47.8	796.1	0.01772	47.8	796.1
	PVC	Deck rods PVC	N	0.00193	2.6	5.6	0.00193	2.6	5.6	0.00193	2.6	5.6
	Aluminium	Ridge	R	0.00074	2.0	33.2	0.00074	2.0	33.2	0.00074	2.0	33.2
	Aluminium	Window frame	R	0.00367	9.9	164.9	0.00319	8.6	143.3	0.00271	7.3	121.7
	Rubber	Window frame rubber	N	0.00019	0.3	1.0	0.00019	0.3	1.0	0.00019	0.3	1.0
	PVC	Window frame PVC	N	0.00036	0.5	1.0	0.00030	0.4	0.9	0.00025	0.3	0.7
	Glass	Panes	R	0.15265	381.6	258.5	0.15370	384.2	260.3	0.15546	388.7	263.3
Total		Total			**1,263**	**2,742**		**1,265**	**2,722**		**1,268**	**2,704**
		New			619	650		618	650		618	650
		New %			49%	24%		49%	24%		49%	24%
		Reuse			644.9	2,092		646.2	2,073		649.3	2,054
		Reuse %			51%	76%		51%	76%		51%	76%

appendix 8

appendix 8

Carbon footprint of a the various types of bracing in modules.

table 1: carbon footprint of bracing (own, 2023)

				Endwall bracing			Sidewall bracing			Midfield bracing			Deck bracing		
Group	Material	Component	R/N	Volume	Weight	Footprint	Volume	Weight	Footprint	Volume	Weight	Footprint	Volume	Weight	Footprint
[-]	[-]	[-]	[-]	[m^3]	[kg]	[$kgCO_{2\text{-eq}}$]	[m^3]	[kg]	[$kgCO_{2\text{-eq}}$]	[m^3]	[kg]	[$kgCO_{2\text{-eq}}$]	[m^3]	[kg]	[$kgCO_{2\text{-eq}}$]
Structure	Stainless steel	Bracing	R	0.00109	8.56	16.35	0.00217	17.06	32.59	0.00161	12.61	24.09	0.00097	7.60	14.52
	Galvanized steel	Bracing strip	R	0.00013	1.05	1.89	0.00035	2.76	4.97	0.00018	1.38	2.48	0.00005	0.40	0.73
	Galvanized steel	Crossbeam	R	-	-	-	0.00330	25.92	46.69	0.00800	62.84	113.17	-	-	-
	Galvanized steel	Crossbeam end plate	R	-	-	-	0.00060	4.71	8.48	0.00062	4.84	8.72	-	-	-
Total					9.61	18.24		50.46	92.73		81.67	148.47		8.00	15.24

appendix 9a

Carbon footprint of the original version of single and coupled growing systems.

table 1: carbon footprint of the original version of growing systems (own, 2023)

				Single system			Coupled system		
Group	Component	Material	N/R	Volume	Mass	Footprint	Volume	Mass	Footprint
[-]	[-]	[-]	[-]	[m^3]	[kg]	[kgCO$_{2\text{-eq}}$]	[m^3]	[kg]	[kgCO$_{2\text{-eq}}$]
Structure	Base foot column	Galvanized steel	R	0.00424	33.25479	59.89188	0.00635	49.88218	89.83781
	Sidearm column	Galvanized steel	R	0.00649	50.92140	91.70943	0.00973	76.38209	137.56415
	Vertical column	Galvanized steel	R	0.02032	159.51907	287.29384	0.03048	239.27860	430.94076
	Corner caps	Rubber	N	0.00244	3.66142	12.63189	0.00366	5.49213	18.94784
	Moment resistant corner	Galvanized steel	N	0.00120	9.42000	16.96542	0.00180	14.13000	25.44813
	Shoring	Galvanized steel	N	0.00051	4.01981	7.23969	0.00102	8.03963	14.47937
	Shoring connection plate	Galvanized steel	N	0.00009	0.68968	1.24211	0.00018	1.37935	2.48422
	Shoring crossbeam	Galvanized steel	N	0.00134	10.49465	18.90087	0.00267	20.98930	37.80174
	M10 bolts and nuts	Stainless steel	N	0.00002	0.13458	0.25704	0.00003	0.26916	0.51409
Container	Container body front	Aluminium	N	0.01819	49.11917	817.34294	0.03638	98.23833	1,634.68588
	Container body bottom	Aluminium	N	0.12328	332.84642	5,538.56435	0.24655	665.69283	11,077.12869
	Propogation tray	Polycarbonate	N	0.10796	129.55307	142.50837	0.21592	259.10614	285.01675
	Clods	Mosswool	N	0.02463	30.78761	67.73274	0.04926	61.57522	135.46548
	Capillary cilinders	Mosswool	N	0.05085	63.56522	139.84349	0.10170	127.13044	279.68696
	NFT plate	Aluminium	N	0.07920	213.84000	3,558.29760	0.15840	427.68000	7,116.59520
	NFT overflow bar	Aluminium	N	0.00006	0.16200	2.69568	0.00012	0.32400	5.39136
	NFT cillinder support	Aluminium	N	0.00121	3.25720	54.19986	0.00241	6.51441	108.39973
	Tray support	Aluminium	N	0.01296	34.99200	582.26688	0.02592	69.98400	1,164.53376
	Irrigation slit	Polycarbonate	N	0.00552	6.62145	7.28360	0.01104	13.24290	14.56719
	M10 bolts and nuts	Stainless steel	N	0.00016	1.24097	2.37025	0.00032	2.48194	4.74050
Drive	Chain link	Stainless steel	N	0.00524	41.11315	78.52612	0.01047	82.22630	157.05224
	Chain sheave	Stainless steel	N	0.00402	31.58399	60.32541	0.00805	63.16797	120.65083
	Sprocket	Stainless steel	N	0.00091	7.14743	13.65160	0.00182	14.29487	27.30320
	Drive belt	Rubber	N	0.00022	0.33365	1.15109	0.00044	0.66730	2.30218
	Chain coupling	Stainless steel	R	0.00035	2.72308	5.20108	0.00052	4.08462	7.80163
	Drive motor mount plate	Galvanized steel	N	0.00031	2.44266	4.39923	0.00031	2.44266	4.39923
	Drive motor shaft	Stainless steel	R	0.00002	0.19267	0.36799	0.00002	0.19267	0.36799
	Drive shaft	Stainless steel	R	0.00090	7.09015	13.54219	0.00181	14.18030	27.08438
	Drive belt shaft holding	Stainless steel	N	0.00009	0.74262	1.41840	0.00019	1.48524	2.83681
	M10 bolts	Stainless steel	N	0.00001	0.09112	0.17405	0.00001	0.09112	0.17405
Light	Cable tube	Stainless steel	N	0.00006	0.43392	0.82879	0.00006	0.46599	0.89004
	Light mount plate	Galvanized steel	N	0.00331	25.99920	46.82456	0.00662	51.99840	93.64912
	Light mount mirror	Aluminium	N	0.00520	14.04669	233.73691	0.01040	28.09338	467.47381
	Shoring crossbeam mirror	Aluminium	N	0.00127	3.43364	57.13569	0.00254	6.86727	114.27138
	Lights	Various materials	N						
Drive	Drive motor	Various materials	R						
Floor	Sliding rails in concrete	Stainless steel	N	0.03309	259.74708	496.11692	0.04963	389.62062	744.17538
Irrigation	Supply pipe	Polycarbonate	N	0.00218	2.61443	2.87588	0.00218	2.61443	2.87588
	Distribution pipe	Polycarbonate	N	0.00012	0.14788	0.16267	0.00041	0.49341	0.54275
	Drain profile	Polycarbonate	N	0.00212	2.54040	2.79444	0.00423	5.08080	5.58888
Total	Total				1,541	12,428		2,816	24,364
	New				1,287	11,970		2,432	23,670
	New %				84%	96%		86%	97%
	Reuse				254	458		384	694
	Reuse %				16%	4%		14%	3%

appendix 9b

Carbon footprint of the improved version of single and coupled growing systems.

table 2: carbon footprint of the improved version of growing systems (own, 2023)

				Single system			Coupled system		
Group	Element	Material	N/R	Volume	Mass	Carbon	Volume	Mass	Carbon
[-]	[-]	[-]	[-]	[m^3]	[kg]	[$kgCO_{2\text{-eq}}$]	[m^3]	[kg]	[$kgCO_{2\text{-eq}}$]
Construction	RHS 160x60x4	Galvanized steel	R	0.03104	243.69525	438.89515	0.04657	365.54288	658.34273
	Moment resisting corner	Galvanized steel	N	0.00060	4.71000	8.48271	0.00090	7.06500	12.72407
	Bumping/moisture cap	Rubber	N	0.00244	3.66142	12.63189	0.00366	5.49213	18.94784
	Bracing turnbuckle	Galvanized steel	N	0.00005	0.36227	0.65246	0.00009	0.72455	1.30491
	Bracing connection plate	Galvanized steel	N	0.00009	0.68968	1.24211	0.00018	1.37935	2.48422
	Bracing cable d10	Stainless steel	N	0.00051	4.01981	7.67785	0.00102	8.03963	15.35569
	Crossbrace beam SHS 50x2	Galvanized steel	N	0.00134	10.49465	18.90087	0.00267	20.98930	37.80174
	M10 bolts and nuts	Stainless steel	N	0.00002	0.13184	0.25182	0.00003	0.26368	0.50363
Container	Tray support	Aluminium	N	0.00360	9.72000	161.74080	0.00720	19.44000	323.48160
	Capillary cillinder	Mosswool	N	0.04450	55.61957	122.36305	0.08899	111.23914	244.72610
	Tray clod	Mosswool	N	0.02463	30.78761	67.73274	0.04926	61.57522	135.46548
	Propogation trays	Polycarbonate	N	0.05303	63.63449	69.99794	0.10606	127.26900	139.99590
	NFT overflow bar	Polycarbonate	N	0.00006	0.07200	0.07920	0.00012	0.14400	0.15840
	NFT plate	Polycarbonate	N	0.03960	47.52000	52.27200	0.07920	95.04000	104.54400
	NFT cillinder support	Polycarbonate	N	0.00008	0.09048	0.09953	0.00015	0.18096	0.19905
	NFT irrigation slit	Polycarbonate	N	0.00324	3.88673	4.27540	0.00648	7.77345	8.55080
	Container belly	Polycarbonate	N	0.05967	71.60357	78.76392	0.11934	143.20716	157.52788
	Container front	Polycarbonate	N	0.00831	9.97048	10.96752	0.01662	19.94095	21.93505
	M10 bolts and nuts	Stainless steel	N	0.00018	1.44931	2.76818	0.00037	2.89862	5.53636
Drive	Chain sprocket	Stainless steel	N	0.00091	7.14743	13.65160	0.00182	14.29487	27.30320
	Chain sheave	Stainless steel	N	0.00402	31.58399	60.32541	0.00805	63.16797	120.65083
	Chain link	Stainless steel	N	0.00524	41.11315	78.52612	0.01047	82.22630	157.05224
	Drive shaft and holding	Stainless steel	R	0.00108	8.48784	16.21177	0.00211	16.55181	31.61396
	Motor mounting plate	Galvanized steel	N	0.00031	2.44266	4.39923	0.00031	2.44266	4.39923
	M10 bolts	Stainless steel	N	0.00001	0.09112	0.17405	0.00001	0.09112	0.17405
	Drive belt	Rubber	N	0.00022	0.33365	1.15109	0.00044	0.66730	2.30218
	Shafts chain coupling	Stainless steel	R	0.00035	2.72308	5.20108	0.00052	4.08462	7.80163
	Drive motor	Various materials	R						
Foundation	Concrete beams	Concrete	N	0.19914	477.94560	488.80800	0.29872	716.91840	733.21200
	Sliding rails	Stainless steel	N	0.02978	233.80440	446.56640	0.04468	350.70660	669.84961
Irrigation	Inflow pipe	Polycarbonate	N	0.00129	1.54913	1.70405	0.00166	1.98629	2.18492
	Draining profile	Polycarbonate	N	0.00071	0.85410	0.93951	0.00142	1.70820	1.87902
Lighting	Crossbrace beam mirror	Aluminium	N	0.00115	3.09943	51.57456	0.00230	6.19886	103.14911
	Light mount mirror	Aluminium	N	0.00520	14.04669	233.73691	0.01040	28.09338	467.47381
	Light mount	Stainless steel	N	0.00331	25.99920	49.65847	0.00662	51.99840	99.31694
	Cable tube	Polycarbonate	N	0.00000	0.00546	0.00601	0.00006	0.07167	0.07883
	Philips GreenPower LED	Various materials	N						
Total	Total				1,413	2,512		2,339	4,318
	New				1,158	2,052		1,953	3,620
	New %				82%	82%		83%	84%
	Reuse				255	460		386	698
	Reuse %				18%	18%		17%	16%