Friedrich-Alexander-Universität Erlangen-Nürnberg
Facultiy of Engineering - Department of Electrical Engineering (EEI)
Chair of Electrical Smart City Systems

Bachelor's (oder Master's) Thesis

on the topic

LPWAN: Deriving the theoretical and practical limitations, and design of an application/ technology matching algorithm

by

Name Surname
born on DD.MM.YYYY in LOCATION

to achieve the academic degree

Bachelor / Master of Science (B.Sc. / M.Sc.)

Supervisor

Prof. Dr.-Ing. Norman Franchi

Second supervisor

Third Supervisor

03.11.2022 (Start) - 03.05.2023 (End)

Declaration

I, _______________ (Name), student registration number:____________, hereby confirm that I completed the submitted work independently and without the unauthorized assistance of third parties and without the use of undisclosed and, in particular, unauthorized aids. This work has not been previously submitted in its current form or in a similar form to any other examination authorities and has not been accepted as part of an examination by any other examination authority.
Where the wording has been taken from other people's work or ideas, this has been properly acknowledged and referenced. This also applies to drawings, sketches, diagrams and sources from the Internet.
In particular, I am aware that the use of artificial intelligence is forbidden unless its use an aid has been expressly permitted by the examiner. This applies in particular to chatbots (especially ChatGPT) and such programs in general that can complete the tasks of the examination or parts thereof on my behalf.
Furthermore, I am aware that working with others in one room or by means of social media represents the unauthorized assistance of third parties within the above meaning, if group work is not expressly permitted. Each exchange of information with others during the examination, with the exception of examiners and invigilators, about the structure or contents of the examination or any other information such as sources is not permitted. The same applies to attempts to do so.

Any infringements of the above rules constitute fraud or attempted fraud and shall lead to the examination being graded "fail" ("nicht bestanden").

____

Erlangen, date

____

name
91054 Erlangen
address

Danksagung

Ich möchte meinem Betreuer Vincent Lassen danken für die offene Kommunikation. In besonderer Hinsicht half er mir mit der Aufbereitung und Präsentation von Informationen. Vielen Dank auch an Tobias Veihelmann der die Betreuung übernahm als Vincent unterwegs war. In der letzten Phase bat er tolle Beratung zur meiner Vorgehensweise und allen Fragen die ich an ihn richtete.

Ein besonderer Dank an Professor Norman Franchi. Er nahm mich mit meinem Themenvorschlag auf. Über die Dauer der Arbeit bot er immer sehr konstruktives Feedback, welches mich in fachlicher und methodischer Hinsicht signifikant weiter brachte.

Sie alle halfen mir persönlich und professionell weiter zu wachsen. Und trugen maßgeblich zur Entstehung dieser Arbeit bei. Dafür bin ich dankbar.

Meine Eltern und meine Schwester stellten jederzeit emotionale Unterstützung bereit. Vielen Dank.

Kurzfassung

Brauche ich eine deutsche Kurzfassung wenn ich auf Englisch schreibe

Abstract

This chapter is under construction.
This work will introduce a plant irrigation system in the form of panels. These panels shall be mounted on building facades and be protected from the elements by an additional layer of glass. With this we can provide all of the benefits over traditional agriculure which have been discussed before. Simultaneously this arrangement addresses the main problem of present vertical farming systems by not relying on a completely artificial environment and instead using existing resources to cultivate the plants. Namely natural lighting by the sun and vertical area of city infrastructure.

Additionally it provides even more benefits resulting from the tight integration into its environment and distributed nature of deployment. double use as building insulation.

This work will introduce a urban farming concept providing clean, regional food while simultaniously providing insulation to existing buildings and improving city climate. The solution presented consists of panels which can be retrofitted on existing building Let us imagine a future city where old buildings have been retrofitted with insulating tiles. These tiles shall - improvement of quality of life factors inside cities such as improved air quality, beautifying building facades and creating awareness for plants and human food production - providing clean, regional food for cities - insulate existing buildings for more energy efficiency and sound isolation - help with regulating city climate during heat waves

Abbreviations and Acronyms

CEA Controlled Environment Agriculture

PAR Photosynthetically Active Radiation

PPFD Photosynthetic Photon Flux Density

DLI Daily Light Integral

NFT Nutrient Film Technique

VPD Vapor Pressure Deficit

SVP Saturated Vapor Pressure

RH Relative Humidity

HVAC Heating, Ventilation and Air Conditioning

LED Light Emitting Diode

KISS Keep It Simple, Stupid

ibd internal block diagram

EC Electrical Conductivity

DC Direct Current

PV Photovoltaic

Contents

Chapter 1

Introduction

Motivation In the last two centuries human civilization has seen tremendous growth, a rise in global interconnectedness and urbanization. These trends are posed to continue at a rapid rate and provide mankind with prosperity never imaginable to our ancestors. Unfortunately as everything in life these developments also come with significant drawbacks, we as a society need to address.

One, interconnectedness comes at the cost of reliance. The division of labor on a global scale has produced the curious situation where some nations are not able to provide food for their own people needs ref. An arrangement which previously has taken down not only nations but entire civilizations needs ref. Something as basic as food supply should be the upmost priority for a government serving its people. However now, agricultural highly productive nations such as Ukraine are exporting much of their produce, providing a stable food supply to the world. But with this we can see two major problems. On the one hand, recent history has blatantly revealed that we live on a global stage with many different actors and their own agendas. Relying too heavily on entities a nation can not control or for which their safety can not be insured, poses a serious concern for said nation. On the other hand, human made carbon emissions will have impacts on the climate which can not be predicted fully. It is certain however, that current climate and weather patterns will shift in many regions of the world. The stability of these systems constitutes a big factor in what makes highly fertile lands the 'breadbaskets of earth'. This dependability can not be relied upon in the future.

But not only security of the food supply is a concern. Humanities resource usage and exploitation of the environment has spelled doom for biodiversity on planet earth. Part of the reason for this huge impact is traceable to our civilizations' land use. Approximately ...% of the earths land surface is occupied by agriculture needs ref. A startling fact considering that the vast majority of people live in cities, which themselves are highly space efficient. Even owing much of their success to the tight integration of people, services and industry. On the flip side these urban spaces will get less livable in the future. They are mostly comprised of concrete, asphalt and glass, trapping much of the incoming heat. This stands in stark contrast to rural areas in which natural vegetation provides evaporative cooling and shade. Current technological cooling solutions are energy intensive and constitute only a remedy for the symptom, not fixing the underlying cause.

These issues are getting addressed slowly and separately for now. To tackle heat buildup in cities, urban greening can be used. This comes in the form of public parks, grassy areas for recreational use and trees to provide shade. But since a lot of city area is already occupied by buildings, this is no solution everywhere. Rooftop gardens and facade greening are a logical next step to increase urban plant density. And indeed indoor temperatures and air quality around buildings following this approach are measurably improved needs ref.

Next, to lessen the reliance and impact of food supply on the climate, Controlled Environment Agriculture (CEA) and in particular Urban Vertical Farming aim to control the plants' environment fully. This enables traditionally less arable regions to take food production into their own hands and grants a number of other benefits. By virtue of growing vertically and optimizing the plant environment, area use is significantly reduced. Need for fresh water is cut to only 5 to 10 % of traditional systems needs ref. And because the plants are entirely kept inside their own artificial ecosystem, pests and therefore pesticides are of no concern. Allowing clean food production transcending even organic standards. Fertilizer can be kept inside this microcosm as well and does not seep into the soil, reducing freshwater eutrophication. Lastly these farms can be deployed wherever there is energy and water infrastructure. This enables to grow food far more regional than possible at the current moment.

Albeit these promising qualities, a green city revolution has failed to materialize so far. Since nature is messy and changes over time, facade greening constitutes an additional burden, without providing a tangible advantage to the building owner. Maintenance in the form of cutting plants and inspecting the integrity of building structure becomes necessary. This work will not illuminate these issues in detail but offers inherent relief by greening with crop plants. They provide economic value and already presuppose a controlled environment for the plants to grow in.

There are two main obstacles which hinder adoption of vertical farming as identified by this study. One: The types of plants which can be grown is limited. Especially when taking profitability into consideration. Mostly leafy greens and microgreens are cultivated to date. Two: The energy consumption is significantly higher than traditional agriculture @barbosa2015. This makes these farms less competitive and shifts resource demand from water and land area to energy. In countries like Germany, where fossil fuels still comprise a significant part of the energy production, this is a notable concern.

Procedure The goal of this work is to drastically reduce the energy requirements of Vertical Farming while maintaining a semi-controlled environment for the crops to grow in. Especially optimal lighting conditions for the plants shall be maintained since illumination accounts for the highest power draw. This is shown later.

To accomplish this goal, first chapter 2 introduces some basic concepts and terminology employed in this work. We will then look at existing commercial and academic vertical farming systems and analyze strengths and deficiencies. As reasoned later in chapter 3, the main issue holding back adoption are high energy usage requirements. This is the basis of the novel concept presented. To minimize energy consumption, natural light shall be used. This is accomplished by retrofitting building facades with the proposed system. This choice directly results in an obvious synergy. Using the vertical farming infrastructure as an outer layer to insulate existing buildings or new architectural projects. To the best of the authors' knowledge, a system like this has not been suggested so far. Integrating vertical farming with building climate control has been proposed before needs ref. However, the paper suggests using the basement for farming. A space which is currently already in use for most buildings. Coming back to this work, section 3.3 stipulates requirements to judge feasibility of the present retrofit concept. Also, metrics to evaluate these requirements are discussed. In section 3.4 the general architecture of the system is constructed and visualized with SysML diagrams. The vision of the architecture is shown via Blender models representing a tangible implementation at Friedrich-Alexander-University. Chapter 4 then implements this example unit in a Modelica simulation. Originating from the feasibility requirements and plant needs, the general simulation architecture is built up. We chose lettuce as the crop plant. Mathematical models describing water use and yield output are implemented and combined as a Modelica model. Building on the work of the Modelica Buildings Library, an investigation into the thermal and energy balances is set up. A simulation of the physical environment is constructed and interactions with the engineered system are taken into account. Section 4.4 compares the resulting energy requirements to current vertical farming systems. A suitable scale for a solar installation will be given and the feasibility assessed. The results are presented in chapter 5. Further evaluation and resulting conclusions are discussed in chapter 6. In chapter 7 the findings are summarized and areas of further interest are laid out.

Chapter 2

Fundamentals

2.1 Thermodynamics

How do I cite best here? Whole section is based on @cengel2003. This work wants to model plant growth and insulation potential. These statements require temperature information. Therefore, this section introduces some fundamentals from thermodynamics. They will make it possible to simulate heat flows and gather necessary data.

2.1.1 Types of Heat

Heat can be classified into two different forms. There is sensible heat which directly causes a temperature change in a material. And there is latent heat which is responsible for the phase change of a material. During the phase change, there is no temperature change from heat added into or subtracted from the system. Total heat transferred during a process is denoted by Q and the rate at which this happens is signified with $\dot{Q}$ carrying the unit Watt. This heat transfer rate $\dot{Q}$ is what we will look at next.

2.1.2 Heat Transfer

Heat transfer can fundamentally occur in three different forms. Conduction, Convection and Radiation.

Conduction This refers to heat moving through a material. It is characterized by the heat conductivity k ($\frac{\mathrm{W}}{\mathrm{m\,K}}$) specific to the substance in question and can be modeled by Fourier's law

$$\dot{Q}_{cond} = -k\frac{A}{L}\Delta T$$

where A (m^2) is the area through which the conduction takes place, L (m) is the distance and ΔT (K) is the temperature difference.

Convection This is heat transferred on the boundary between a solid and a fluid. The characteristic value for this interaction is the convection heat transfer coefficient h ($\frac{\mathrm{W}}{\mathrm{m^2\,K}}$) while the mathematical description is given by Newton's law of cooling

$$\dot{Q}_{conv} = hA\Delta T$$

with A being again the area, and ΔT the temperature difference.

Radiation This describes heat transfer via electromagnetic waves. This property can be emitted or absorbed. Any material possessing a temperature greater absolute zero will emit some heat to its surroundings. For a black body – an idealized concept absorbing all incident radiation – this heat flux density is given by the Stefan-Boltzmann Law. For real materials the emissivity ϵ (-) and the objects' surface area A are taken into account to get

$$\dot{Q}_{rad} = \epsilon\sigma A(T^4 - T_{surr}^4)$$

where T (K) is the material temperature, σ ($\frac{\mathrm{W}}{\mathrm{m^2\,K^4}}$) is the Stefan-Boltzmann constant and T_{surr} (K) describes the temperature of an idealized sphere infinitely far from the object. When taking about incoming radiation, we have the characteristic value of absorptivity α (-). This is combined with the incident radiation $\dot{Q}_{inci}$ (W) to obtain

$$\dot{Q}_{abso} = \alpha\dot{Q}_{\mathrm{inci}}$$

for captured heat flux by a material.

2.1.3 Other relevant thermodynamic properties

Heat Capacity.
Heat transfer via mass transfer.
Shall I put references here for what the fundamentals are needed? Like latent heat to determine evaporation cooling, mass transfer for ventilating?

2.2 Agricultural and CEA Basics

As the name suggests, Controlled Environment Agriculture is about controlling the environment of a crop. So what needs to be managed to provide a habitat for these green organisms? This can most easily be answered by abstracting the plant down to the process of photosynthesis.

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

The output we usually care about when growing crops is glucose $C_6H_{12}O_6$ as well as more complex carbohydrates built up from this constituent. After water, these make up the bulk of the mass of the plant. This is the reason to optimize this process. As we can see, there are two chemical inputs necessary. Water is taken up by the roots, so *Irrigation* is required. Carbon Dioxide diffuses into the leaves from the surrounding air and so the plant benefits from a controlled *Atmosphere*. Additionally, there is another input not directly apparent in the equation. Since photosynthesis is an endothermic reaction, energy needs to be supplied. This is done with *Illumination*. These are the three domains on which technological solutions hinge to provide optimal control.

2.2.1 Illumination

For illumination two foundational notions have an influence on the plant. Instant irradiance and the characteristics on how this instantaneous value is supplied over time.

Instant Irradiance

The instantaneous radiation can further be divided into light spectrum and intensity for our application. The two concepts Photosynthetically Active Radiation (PAR) and Photosynthetic Photon Flux Density (PPFD) quantify these qualities for natural and artificial sources respectively. They both carry the same unit ($\frac{\mu mol}{m^2\,s}$) and except for their origin, can be treated the same. As their name implies these values characterize the radiation which can be used in photosynthesis.

Light Spectrum Plants use light in the spectrum from 400 nm to 700 nm needs ref. This is only a portion of the natural solar spectrum which is hitting earth. Luckily a simple conversion factor exists to convert the suns' radiation usually provided in $\frac{W}{m^2}$ to PAR @reis2020.

For artificial radiation you are able to choose a light source with specific spectrum characteristics. This used to be more constrained in the past, but the proliferation of LEDs allows for fine-grained adjustments of light quality. Sources catering their spectrum specifically to the photosynthetic range are widely available. And so we can take the light output right as PPFD.

Light Intensity Natural light and how to calculate the intensity on a tilted surface.

Time Aggregation

When assessing the optimal lighting conditions for plant growth, several factors need to be illuminated. Lol illuminated. Light spectrum, Instantenous light intensity, Cumulative light amount and Photoperiod

To quantify the *cumulative light amount* and *photoperiod* for a whole day, we simply accumulate PAR and PPFD over this interval. This is called Daily Light Integral (DLI).

For artificial lighting, the spectrum will lie inside the photosynthetically active spectrum, since they are made specifically for plant cultivation. And so the ppfd is taken directly. Further optimization can be done by adjusting the red, green, blue ratios. This is not taken into account however, since we will illuminate human inhabited areas. Therefore, white light is chosen to not disturb the inhabitants of the building with irritating light colors.

LEDs are chosen because of their high efficiency and possibility to adjust the light spectrum granuarly.

Typical values for solar radiation and artificial illumination.

2.2.2 Irrigation

Water and Nutrients in CEA are mixed and delivered to the plants directly by a process known as fertigation. For the most part the roots are taken care of directly, without the use of any soil. Substrates such as rockwool or perlite provide alternatives but are no necessity. This soilless method of cultivation is referred to as *Hydroponics*. Hydroponic systems use less water and enable greater plant densities than traditional agriculture. They offer high consistency and a tight control on water and nutrient delivery.

Multiple different techniques like Nutrient Film Technique (NFT), deep water culture and *Aeroponics* have developed over the years for differing use cases. Aeroponic systems are special, in that the roots of the plants are not submerged in water. Instead, they are surrounded entirely by air and either sprayed or misted with fog. This relieves two of the main problems with hydroponics. Disease and aeration. In case of a single infected plant, the disease can be carried by the nutrient solution to the whole system without proper sterilization. In aeroponics all roots are sprayed with fresh solution, therefore contamination does not spread easily. Additionally, as the underground part of the plant does not perform photosynthesis but certainly needs oxygen for cellular respiration, water in hydroponics needs to be aerated. This can obviously be dropped if the root zone is suspended in air already. Because of this enhanced gas exchange, in theory a wider variety of plants can be cultivated compared to systems which submerge the roots in water. However, roots dry out quickly and plants die in case of a malfunction. Therefore, this technique is not industry standard and generally has tighter requirements for control.

For this work we will employ an aeroponic system because of the lightweight nature and high flexibility. The strong requirement for control will be alleviated by the use of separate units – the plant panels – compartmentalizing any damage potential.

Explain Electrical Conductivity (EC) and pH.

2.2.3 Atmosphere

As elaborated before, optimizing photosynthesis -> chemical components.

Optimizing the atmosphere in CEA boils down to one procedure. Enhancing photosynthesis. There are two chemical inputs required to make this process happen. CO_2 and H_2O.

CO_2 is quite straight forward. The availability to the plant can be enhanced by elevating concentration in the surrounding air. This is not necessary of course, but is routinely done to increase yields in greenhouse settings. Secondly the plant needs *water*. However only a small amount of water is actually used in metabolic processes such as photosynthesis. About 99 % of the H_2O is actually transpirated needs ref to continually move nutrients up from the roots. This is historically modeled for crops by a process known as evapotranspiration. Combining evaporation from the soil and transpiration of the plant body. Since we are not dealing with soil, we only need to look at transpiration. The characteristic concept capturing this process into a single value is Vapor Pressure Deficit (VPD). *VPD* (kPa) describes humidity and temperature of the air. It is calculated by first computing the Saturated Vapor Pressure (SVP) (kPa) for a given temperature T (°C),

$$SVP = 0.611e^{\frac{17.27T}{T+237.3}}$$

and then using Relative Humidity (RH) (%) to obtain

$$VPD = SVP \times (1 - \frac{RH}{100}) \quad \text{@howell1995.}$$

VPD and SVP cursive everywhere or straight in the equation? What's the convention?

High VPD means dry air. Too high and the plant will close its pores to limit water loss, restricting photosynthesis. A low value suggests that the air is already saturated and transpiration is also impeded. Typical values range from ... to ... and the ideal value depends on the crop and its growth state.

Our concept will not implement carbon dioxide enrichment, since the farm air will interface with humans in the building. CEA facilities also oftentimes spend significant resources to condition the air with Heating, Ventilation and Air Conditioning (HVAC) systems. Following the theme of minimizing energy consumption, passive air cooling is chosen.

Other notable qualities of the atmosphere include air temperature, air speed and humidity. These foster mostly the health of the plant and will not have a significant impact on photosynthesis. Temperature and humidity in this field is usually described as the single value of VPD.

Chapter 3

Theoretical Analysis and Approach

This chapter presents an analysis of the system and literature regarding previous research. It will segment different subsystems to separate the controlled system, the engineered system and the environment they are deployed in. With the analysis done, we will have a clear understanding of relevant parameters and their interaction. Which will be the basis for a sensitivity analysis to determine the most impactful components. From this the main goal of this work is extracted. Knowing the objective and the most influential elements enables us to map out a solution proposal. It also prepares us for the simulation brought fourth in chapter 4.

First introduce the system and what is important, so the reader understands current implementations. Then prune the system to sculpt our concept.

3.1 System Analysis

To design a solution, we must first know the structure of the problem. For this we need to get a tangible definition of the term system. For the engineer, it can be described as a collection of elements with properties of interest @schmitt2019. Following this definition, we need to identify the systems' constituents. And then analyze what about them is important to us. The next section will break down the different parts.

3.1.1 Partitioning

The primary classification is to distinguish between controlled system, engineered system and context. The plant is the basis of the *Controlled System*. However, it is not possible to manage it directly. We need to interface with its environment to affect these green lifeforms. This environment is further divided into leaf and root surroundings, since they require different conditions. Apparent from their different situation in nature.

Going back to the fundamentals of CEA, the *Engineered System* is composed of three parts. Illumination, irrigation and the atmosphere control. They cater to the different needs of the plant. Atmosphere control and illumination interface with the leaf environment, while irrigation takes care of the root system. Together the controlled system and the engineered system make up, what we will call a 'farm'.

These parts are embedded into a greater *Context* they need to operate in. This is where this work diverges from previous concepts. In the past, the field has tried to shield the farming context from outside influences. Less exchange to the environment means a very high level of consistency and independence. As we will see in the analysis of commercial farms (3.1.3), this approach has not proven successful though. This is why this work embraces the context it operates in. Seeing it not as a hindrance but as an opportunity for synergy. As introduced before, this work places the farm on building facades. Two different domains reveal themselves in this context. The building insides and the city environment. The *City* in this work is classified as everything surrounding the envelope of the farm. Therefore, the outside world with weather and the suns' radiation is integrated here and enables a hybrid approach to plant cultivation. Part utilization of natural resources and part artificial optimization of the environment. Similar to how greenhouses operate already. The interface to the *Building* is novel. Potential for insulation naturally comes to mind, which provides a big benefit not exhausted in this work. We will only evaluate insulation performance. Energy savings for the building brought about by this choice are not considered in the energy balance built up in later chapters.

These are the general parts which comprise our concept. In the next section we will delve deeper into their interactions. They will make up the properties of interest which are still missing for our system definition (3.1).

3.1.2 Properties of Interest

Controlled System

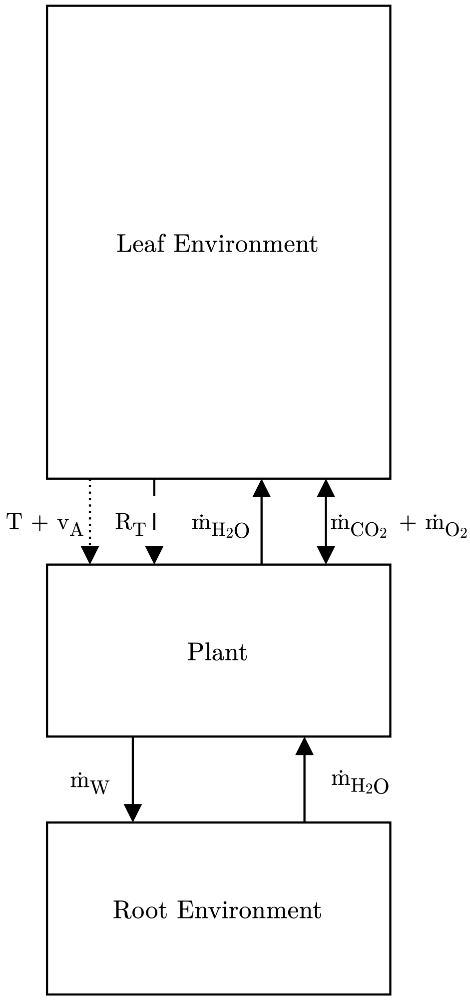
Beginning with the system we want to control, we illuminate the interface between the plant and its environment. The root system is relatively straight forward to manage. We need to supply water and nutrients while cleaning out waste products. These are modeled as mass flows. Water and substances dissolved within it are named $\dot{m}_{\mathrm{H_2O}}$ in this work. The waste products are captured with $\dot{m}_{\mathrm{W}}$.

Shifting up to the leaf environment, photosynthesis presupposes two mass flows as well. Carbon dioxide $\dot{m}_{\mathrm{CO_2}}$ moves from the air to the leaves, while oxygen $\dot{m}_{\mathrm{O_2}}$ diffuses out to the atmosphere. During nighttime these flows are reversed to accommodate cellular respiration. This is however not everything happening at this interface. Most of the water taken up by the roots is actually not used in photosynthesis at all. The plant uses it to carry nutrients up into its body. This movement is fueled by transpiration. About 95 % of the H_2O is carried out to the environment this way needs ref.

Next, energy in the form of radiation is required. The total radiation hitting the leave surface is characterized by R_T. This incorporates the spectrum and intensity of the light. With this we have captured properties which flow from one system to another in the targeted context. These are however not the only attributes of interest.

As shown later in the Yield Analysis there are two other features of the atmosphere we need to take a closer look at. Air temperature T and air speed v_A. These are inputs to the yield model we will introduce in the Yield Analysis. They are not flowing from one system to the other in a physical sense. Instead, these are properties informational in nature. A block diagram of the plant and its immediate environment can be seen in figure 3.1. Mass flows are shown as solid lines, energy fluxes dashed and data flow as dotted lines. Now that we have defined the objective of our inquiry, the next section will talk about its supervision.

Figure 3.1: The plant and its immediate environment.

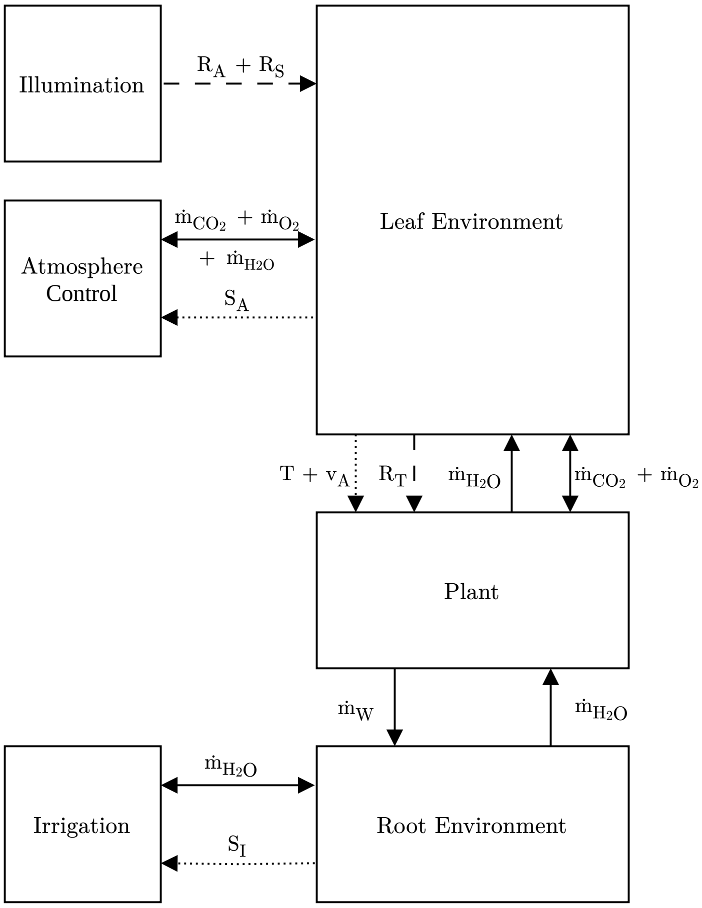


Engineered System

Following the partitioning, the first technical subsystem is illumination. At first thought it seems like we can interface with the plant leaf directly here. However, we only supply a certain PAR / PPFD to the environment. The plant is free to use any amount of it and will actually close its stomata – the pores enabling gas exchange – in light stress situations needs ref. Effectively caping the light it uses. And so the artificial radiation R_A flows from the light source to the leaf environment. Another influence we can take on lighting is to shade the plants from excessive natural lighting. This is frequently done in existing greenhouses to prevent aforementioned light stress. The amount of light passing through will be called R_S. This can be unimpeded or diffused natural radiation by shading.

Next let us look at atmosphere control. Heat flow to heat or cool the air volume is missing. Heat output from LEDs missing. The mass flows $\dot{m}_{H_2O}$, $\dot{m}_{CO_2}$ and $\dot{m}_{O_2}$ introduced before can all be controlled discretely. Water in the form of humidity is an important factor to control VPD as introduced in the Agricultural and CEA Basics. And elevated levels of carbon dioxide promote mass accumulation and therefore higher yields. Oxygen is nonessential in our inquiry and is only distinguished to keep an equilibrium of elements in the leaf environment. For the control to function there needs to be some form of feedback. Sensors to capture the relevant properties temperature, air speed and mass concentrations for water and CO_2 are placed in the air volume. Note that carbon dioxide is usually measured as a volume concentration. But, it is easy to convert these two values via the density. And so no distinction is made in this investigation. Water in the form of humidity can be measured both as a mass or volume concentration. The sensor data is aggregated with the atmosphere control signal S_A.

Figure 3.2: The technical system and its influences.



For irrigation, we describe the water flow with any dissolved materials as $\dot{m}_{H_2O}$. Different to the water mass flow from the root zone towards the plant, this includes the waste products. This is because at this point the pure waste products of the plants will be dissolved and transported together with the water flow. VPD of the root control volume is fed back through the irrigation control signal S_I. With this we have gathered an overview of the attributes needed to govern the controlled system.

Figure 3.2 shows the influences the technical system takes on the controlled system. Subsequently, the next section introduces the setting in which this system is placed.

Context

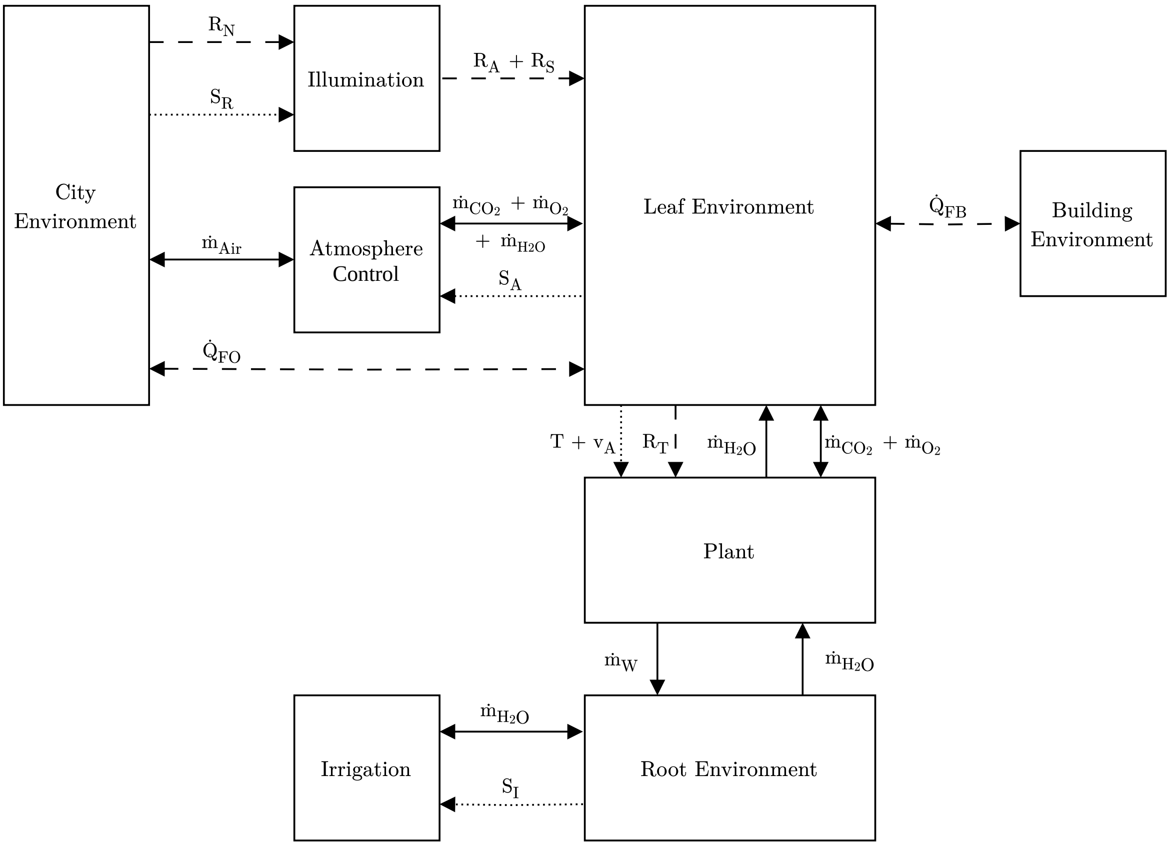
As established before we divide the context into two domains. First we examine the urban environment. Natural radiation R_{N} by the sun illuminates the city and therefore the farm. We discussed before that this can be managed to a certain degree by shading our leaf environment. So this illumination from the city domain interfaces with the corresponding control system. We still need an input signal for the light management. It makes sense to choose the incoming illumination flux as our radiation control signal S_{R}. Since it determines how much shade or supplemental light is needed. Next the atmosphere control can interface with the city environment by exchanging air $\dot{m}_{\mathrm{Air}}$. This can be in the form of opening windows or a more complex interaction when processing air with HVAC units. Apart from the material choices, heat transfer from the farm to the outside $\dot{Q}_{\mathrm{FO}}$ is not something we can actively control. And so it is shown as an energy flux between the building and leaf environments. Note that the name $\dot{Q}_{\mathrm{FO}}$ does not imply a direction of flow. This is already taken care of by the direction of the arrows. Other than introduced in the fundamentals on Heat Transfer, $\dot{Q}$ only includes conduction and convection. Radiation is separated from the other heat transfers because it is special in our application and already modeled with R_{N}.

The important interaction taking place between the farm and the building interior is also a heat transfer $\dot{Q}_{\mathrm{FB}}$. The full block diagram of the system can be seen in figure 3.3. This gives a good overview of what parts and properties are interesting when designing a concept for this application. However, interest does not automatically imply necessity. Fully controlled systems struggle to be profitable as teased before. Engineering is oftentimes about making compromises, so we have to analyze which features of the system are the most relevant. This will enable us to make the right concessions and focus on the most impactful characteristics. These themes are the topic of the next section.

3.1.3 Sensitivity

The first part of this section will establish why the energy demand is an important attribute in this endeavor. Then it will go deeper into which systems are the culprits for high power draw. From this we will then formalize the main goal of this work, which is to minimize energy consumption. Next the sensitivity of parameters influencing yield

Figure 3.3: System partitioning and important flows.



will be discussed. This provides an understanding on which compromises are the least harmful to economic performance of the farm. This constrains the main goal with an auxiliary condition. Maximizing yield. In the end this analysis lays the foundation on the choice of which parameters are free design variables. And which are restricted by the application.

Energy Analysis

Commercial Farms In recent years, hype surrounding vertical farming has slowed significantly. 2023 marked a 91 % decrease in capital investment compared to the year before, according to Pitchbook. Multiple commercial endeavors declared bankruptcy. How do I cite recent developments? Like companies going out of business? Especially in Europe where Energy prices surged in the last years. One notable example is InFarm – a Berlin startup which was able to gather significant funding. Despite the financial backing, all European branches have seized operation. They restructured and continue to function in the Middle East, where energy is less of a concern than water scarcity. The company itself has cited high cost from energy consumption as the primary reason. A focus of the company was to diversify the crops which can be cultivated. Exemplified by their efforts to grow wheat, a plant which has not been demonstrated in this setting before.

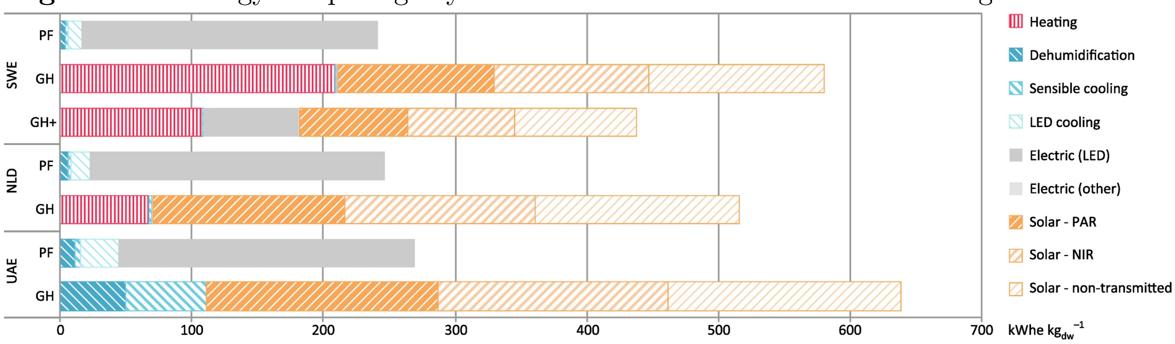
Aerofarms is another big player which recently filed for bankruptcy. During this process they needed to refocus their efforts on their only profitable farm. Both companies focused on a highly controlled and automated approach to farming. This of course is great for reproducibility and quality. But as happens frequently, tech companies want to optimize. And since each plant can have drastically different requirements on the optimal condition, they invested heavily into R&D. Some amount of research is undoubtedly required to compete with traditional agriculture. However, optimization is endless and only offers diminishing returns the further it goes. It is easy to end up with an overengineered system. The author of this work is a proponent of KISS principles. And so the most impactful factors should be considered first. Nature is utilized to nurture the parts deemed less important.

From the examples presented above two lessons can be drawn. Firstly it makes sense to focus on one profitable crop in the beginning and optimize for that. Lettuce is chosen in this work. It is a staple crop for the majority of farms and the most researched in this context. Secondly **Energy consumption needs to be minimized significantly**. The next paragraph examines which systems provide the biggest leverage to achieve this goal.

Research As depicted in figure 3.2 the technical implementation consists of three main subsystems. We will group energy consumers according to this classification. Surprisingly there exists limited data on which part demands the most power. This is because these farms come in a variety of different forms and sizes and the field is still evolving. For example atmosphere control in the form of HVAC has high upfront investment cost. This only makes sense when the operation reaches a certain scale. So not every farm will employ it. The implementation of irrigation can take very different forms as well. We introduced a few methods in the Fundamentals (2.2.2), but there are many more with varying levels of complexity and therefore energy demands. Additionally, requirements for different crops can skew the results one way or the other. For example basil needs more light and subsequently has higher power draw for this subsystem. Furthermore the location of the farm is also a factor. When located in a hot and dry climate, the air conditioning will behave very different from a cold climate in Sweden for example.

For our analysis, we chose two studies looking at lettuce cultivation in different climate conditions. Figure 3.4 shows the resulting energy requirements from @graamans2018. We focus on the bars labeled PF, for plant factory. In contrast, GH stands

Figure 3.4: Energy use per kg dry matter in different climate conditions @graamans2018.



for greenhouse. These farming methods were analyzed for Sweden (SWE), Netherlands (NLD) and the United Arab Emirates (UAE). We will look closer at the Dutch data, since the climate is the closest to Germany. As we can see the vast majority of electricity is used for illumination by Light Emitting Diodes (LEDs). The cooling for this lighting system comes in second and third is dehumidification. Cooling and dehumidification are the realm of atmosphere control. Irrigation is not considered in this study.

Another study @arcasi2024 analyzes the sensitivity for different amounts of lighting and temperatures. Copenhagen and Naples were the closest locations to Germany examined in this paper. They come to a similar conclusion as illumination consumed between 65 to 85 % of electricity. 10 to 20 % can be attributed to HVAC systems. Once again electricity use of irrigation was not considered in this study. However, a whitepaper by the Association of Vertical Farming @zeidler2017 and anecdotal data for example from iFarm suggests that the consumption is negligible. They find that illumination together with air management make up 95 to 98 % of the total energy demand of vertical farming systems. In the further analysis, it is assumed to be inconsequential.

This knowledge now determines the main design choice of the conceptualization. Illumination is by far the biggest contributor to electricity need and so natural lighting shall be used. Now one could argue that a vertical farm like this would offer no advantage over traditional greenhouse cultivation. However when looking at the energy consumption data for greenhouses (GH) in the Netherlands (NLD) shown in figure 3.4, we can see that the power demand largely originates from heating. The solar energy is supplied by the sun and does not need to be taken into account. High power draw from heating makes sense in a greenhouse context. The advantage of this cultivation method is to extend the growing season. So in colder months it needs to be kept warm artificially. However, a greenhouse is surrounded by badly insulated glass. Furthermore, it has a wide interface for heat loss to the ground. When placing the farm on the side of buildings, a distinct advantage emerges. One of the big outside surfaces is no longer exposed to heat loss. Instead, the building now provides heat gain to the farm. Room temperatures humans are comfortable with are usually around 18 to 21 °C. Higher than what lettuce needs to grow. The effectiveness of this will be shown later in the Showcase of Example Unit and Simulation. The interface for heat loss to the ground is minimized as well. And of course other advantages like more regional production – right inside the city – remain. Next, the factors influencing yield will be examined. This will determine what subsystem shall retain optimal control and which will be no focus of this work.

Yield Analysis

With the yield analysis we want to find out which input will produce the biggest difference in plant production. As mentioned before irrigation is a solved problem and this system is assumed to provide water and nutrients in an optimum manner. We will go off of a lettuce model to see which inputs the system deems important. The inputs are air temperature, CO_2 concentration and Photosynthetically Active Radiation. It is difficult to make consistent statements about the influence of the parameters. Since the optima change for different combinations of inputs.

When examining yield, we first need a definition of what is meant by that. It depends largely on the crop under investigation. The fruiting body, roots, leaves or even whole plants can all be considered produce in different contexts. As argued before, we chose lettuce as our crop. For this food item, basically the whole plant can be sold and so yield will be roughly equivalent to weight. The yield model implemented in the later chapters was first proposed by @van_henten1994. It measures yield by modelling dry weight of the plant. For this, mass is split up into the state variables structural x_{sdw} and non-structural dry weight x_{nsdw}. The model is composed of two nonlinear ordinary differential equations. The development of these two state variables is given by

$$\begin{aligned}\frac{\mathrm{d}x_{nsdw}}{\mathrm{d}t} &= c_\alpha f_{phot} - r_{gr}x_{sdw} - f_{resp} - \frac{1-c_\beta}{c_\beta} r_{gr}x_{sdw} \\ \frac{\mathrm{d}x_{sdw}}{\mathrm{d}t} &= r_{gr}x_{sdw}\end{aligned}$$

with parameters c_α (-) being the conversion rate of CO_2 to CH_2O and c_β (-) representing the yield factor. f_{phot} $(\frac{\mathrm{g}}{\mathrm{m}^2\,\mathrm{s}})$ describes gross canopy photosynthesis, f_{resp} $(\frac{\mathrm{g}}{\mathrm{m}^2\,\mathrm{s}})$ the maintenance respiration and r_{gr} $(\frac{1}{\mathrm{s}})$ the specific growth rate. The whole model is too extensive to be shown in this section and so only the top level equations are presented here. What is important for the investigation at hand are the dynamic inputs which influence this model. These are air temperature, CO_2 concentration and Photosynthetically Active Radiation. In the implementation 4.2.1 the whole model can be seen.

There are two ways to gain more information about a system. Running experiments in real life and simulating the system with a model. @van_henten1994b followed up with a sensitivity analysis of the proposed model. They found that radiation has the highest influence very closely followed by CO_2 concentration.

We choose one crop to optimize, however it is assumed that similar dynamics also play a role in other plant species. This is important, since this work tries to establish a general system. It does not aim to overfit to a specific crop type. This is why the energy impact of existing farms will be weighted more heavily than the yield analysis.

Lettuce is chosen for a few different reasons. Firstly it is well suited to aeroponic cultivation needs ref. Secondly it grows quickly and consequently is more economically viable as for instance grain crops. This makes it one of the most used and researched crops in academic and commercial domains alike. Most of the different varieties of lettuce have similar growing conditions, hence no differentiation is made in this work.

Now that we have a system we want to optimize, we need to analyze it more deeply. There are two ways this can be accomplished. Real plants in experiments and models in simulation.

Temperature is a factor we need to control, to achieve an advantage over traditional agriculture. Otherwise, non-competitive.

Experiments For *experiments* we look at available literature. Some paper suggests light spectrum has an even bigger impact than illumination magnitude. As discussed in the fundamentals we do not consider altering spectrum however.

Simulations For *simulations* we implement a lettuce yield model proposed by Van Henten @van_henten1994 in Modelica. The model is a system of nonlinear partial differential equations check if actually right. A follow-up paper @van_henten1994b assessed the sensitivity of the input parameters. Their analysis showed the highest impact for radiation and CO_2 concentration. Radiation displayed slightly more effect on growth. This is mostly consistent with the experimental data discussed above.

Instert picture of plant model.

Water and nutrient delivery is mostly a solved problem in moderate climates and specifically CEA contexts. Hence, it does not play a role in the yield calculation. The properties of interest in the atmosphere are temperature u_T and CO_2 concentration u_{CO2}. For illumination, PAR u_par is considered. As is convention in control settings, inputs are labeled with u and outputs with y.

Plants come in a variety of different forms and varieties. Lettuce is chosen because it is the most researched in the field. To judge crop yield, which factors are important. We present a yield

To be able to judge which factors influence plant yield, we need As @esmaili2020 showed, highest variance for lighting, suggesting most impact to yield.

To minimize energy consumption we have already found above Lighting provides the biggest leverage. This was a priority when designing the system. Similar to greenhouse cultivation, natural light shall be used. But what impact does this have on insulation potential and maximizing yield. For insulation there is none.

Let us analyze what elements enable us to maximize yield. Yield is produced by the plant, so let For this we will introduce the Yield model for lettuce. Input block diagram plant model and interactions.

Water and nutrient delivery is mostly a solved problem. This is why it is not taken as an input to the yield model. We will deploy an aeroponics system as reasoned in the fundamentals 2.2.2.

The Energy Analysis 3.1.3 has shown that illumination in this context takes the highest amount of resources. The optimal lighting conditions can be achieved with reasonable complexity increase. One reason to optimize the lighting.

For the atmospheric conditions For greenhouses, common practice is to elevate levels but keep windows open. As this work is in the context of sustainability, it is not considered supplementing CO_2.

From the first point we can deduct t

We will define this by the functions the system needs to provide.

So what exactly is it this work tries to achieve and what are relevant properties? On a high level This work wants to demonstrate the feasibility of a system. This work wants to advocate, that greening the future city environment and making food production more resilient and better for the climate can be combined. It shall be determined if it makes sense to put plants on buildings. We want to take care of a plant.

The plant is a system we can not control directly. However, indirectly there exists significant potential to optimize the plant environment.

Define plant system.

Definition System. To understand what is needed of a system we first need to define its boundaries. And interactions with adjacent systems. Context in which it is situated. Define scope which we can control.

Yield model highly nonlinear. Difficult to analyze. Additionally, very slow systems with dead time basically impossible to control via classic control theory needs ref.

For humidity / vpd, there could be no data found comparing the sensitivity to the other parameters. It is assumed that enough air exchange will happen from the farm to the outside air to achieve reasonable growth. This is what happens in greenhouses anyway.

3.1.4 Conclusions from the analysis

The energy analysis showed that we need to focus on the lighting for minimizing energy. As a result natural lighting will be utilized. From the yield analysis the result was that again we need to focus on the lighting. As a result we provide a lighting system for the farm to supply optimal DLI to the crop. Additionally as HVAC systems are expensive compared to LEDs – another reason to not focus on atmosphere control for now.

The last section defined the system in question clearly. It showed the most impactful parts. With this knowledge, we can prune the system description to arrive at our concept. It is pretty similar to the system design proposed before but now only showing the parts which actually will be implemented. The atmosphere control will no longer distinguish between the mass flows of different elements. Instead, we accumulate them together to the mass flow $\dot{m}_{Air}$. As we also do not consider control for the air temperature, we remove the heat flow from the atmosphere control.

3.2 General Concept

From **??**, we have a clear picture on the electrical and control systems necessary. However, for a complete implementation some secondary functions need to be fulfilled. For example an atmosphere control absent an envelope to keep the air in, hardly makes any sense. Additionally, we need to supply energy to the systems and provide a structure to mount everything. From the chosen crop – lettuce – there also follows a high turnover rate. It is usually ready in four to six weeks. Therefore, easy mount and demount necessary. These supporting components to the system as well as the tasks of the main system will be formalized and presented in the next section as functions.

3.2.1 Functional Architecture

Definition of our scope, extracted from the analysis. The functions our concept shall serve, breaking down the goals of minimizing energy consumption and maximizing yield.

- Supply optimal lighting conditions.
- Provide a reasonable temperature range to grow lettuce.
- Maintain sufficient air exchange to keep CO_2 and humidity levels in check.
- Sustain optimal water and nutrient delivery.
- Serve a mounting structure to be able to retrofit the system onto buildings.
- Provide transportation mechanism to easily harvest and replant the crops.

Defining what is out of scope makes it easier to understand. Functions which shall **not** be implemented.

- Provide optimal CO_2 concentration.
- Provide optimal temperatures.
- Provide optimal light spectrum.
- Provide optimal humidity levels.
- Provide .

Now that we have gathered an understanding of the system and the scope that this work targets.

Energy system does not serve a particular function. It is a secondary function enabling the functioning of the other functions.

Water tanks to store water. Pumps can run during the day when solar output available.

3.2.2 Structural Architecture

SysML offers a standardized way to convey system information. It offers an informational model as well as a visual representation for systems engineering. Therefore, it will be used to present the concept. There are different diagram types, structural diagrams are used. More specifically the internal block diagram (ibd) is used. This type is taken to describe a systems constituents. The different parts are pictured by rectangles. Connections have a diamond shape on the part which is deconstructed into its constituents. The arrow points to the components. For a full system design, there are a myriad of diagram types to be used in SysML. However, this work will not concretize to deeply and therefore only use this one diagram type. This will enable us to describe the proposed system. From the main system description and the other secondary functions the system needs to provide, we can now extract the structural architecture more easily.

For the structural architecture we will go off of two things we developed so far. Firstly the main system from our system definition (**??**). Secondly the functional architecture with all the systems needed to support the functioning of the main system. This distinction is a little bit arbitrary but needs to be made at some cut-off point. For example the system description could include a system for planting and harvesting, since it is technically needed to convert the plant to economic output. However, the system description grows to large for this work in this way. And so main functions and supporting functions are distinguished. The order these will be introduced roughly follows a spatial line starting from the building and attaching the systems going outward to the city. For comprehensibility's sake, we will present the architecture going spatially from the building to the outside. This will be represented with more foundational components to the left of the diagram. The introduction of these blocks will follow a particular pattern. First the function of the block is presented, then requirements laid out and then the structure of the subsystem is presented in written and visual form. If useful a 3d model is presented to visualize the architecture with a tangible example.

Following the theme of going from the building further outside, let us first get a look at the building in question. It can be seen in 3.5. The pictures of the building faces were made by the author. The 2d plane the model sits on was taken from a satellite image in Google Maps am I allowed to do this?. The 3d geometry data is taken from needs ref.

Figure 3.5: 3d model of the EEI-tower.

Load-Bearing Structure

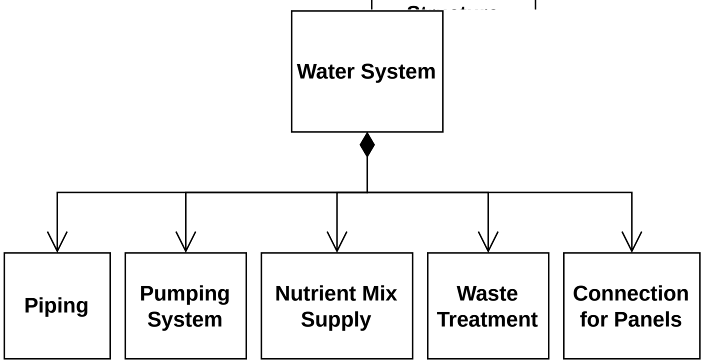
With this in mind, let us first discuss the mounting structure. Its function is to provide a load bearing foundation for any other subsystem to attach to. One point to note is that the system shall be retrofitted to existing buildings. Therefore, it should be self-contained in supporting its own weight. Building faces are very diverse, so it should be independent of the present structure. Of course, it needs to be closely matched to the existing building because the panels are only mounted on the facade. The mounting provides the interface for other subsystems. The pipes, panels and transportation system are part of different components and are defined later. Need to fit to presentation pattern.

Water System

The next system that would need to be installed is the water system. It does not have a direct equivalent in our system description from ??. There we already presupposed the water and nutrient mix to be prepared and available to the irrigation system. The water system will take care of this task. Preparing the nutrient mix and optimal EC and pH-levels. This mixture is then supplied to the panels. It needs to interface to the actual irrigation system illustrated by the component 'connection for panels'. As discussed later we will also utilize a solar array. It makes sense to pump the water during the day up to a water storage on the roof of the building. During nighttime gravity will provide water pressure to the system. A connection to the water system of the building is also conceivable. To keep the retrofit concept minimally invasive though, a separate water circuit is proposed here. Need to fit to presentation pattern.

Figure 3.6: The load bearing structure.

Figure 3.7: The water system mixing and delivering the nutrient mix.



Plant Panels

For the actual irrigation system, we will go into a little bit more depth. As a general concept, they are chosen to modularize the whole system. Providing a standardized platform for any building. One could imagine around three different sizes to best accommodate the space available on the facade. Additionally, they provide smaller compartments to take care of. This is important as discussed before to stop the spread of plant diseases. As well as providing fine-grained control of the plants. Ideally you would want a control system taking care of every plant individually. This however entails high cost and a trade-off needs to be made similar to the lessening of automation in CEA. The modularization makes it possible to stagger planting and harvesting. Now that we have a rough outline of what we want the system to look like – the framework – we can take a closer look at how and what shall be implemented. As discussed before, the panels shall take the role of irrigation. For this they need to provide a closed volume for the root zone. This is the main structure of the presented panels. As detailed in 2.2.2 the system will use aeroponics. This of course can be exchanged for any other hydroponic strategy inside the panels. For example one could imagine NFT channels inside the same panels in which the plant roots reside. For the aeroponic system, a ultrasonic piezoelectric vaporizer is placed in a water filled upper part of the panel. This sustains a fog holding moisture and nutrients inside the root environment. This technology of course is not perfect. Anecdotal information suggests that these vaporizers will crust up with salts dissolved in the water over time. They also heat up the root zone. Root zone temperature is considered separately from the main air temperatures in some studies. Suggesting that it might be an impactful parameter in plant growth and health. This work did not analyze this further though as the general concept of the panel can be the platform for different irrigation strategies. The root volume is controlled according to the system design with a feedback control. A humidity and temperature sensor supplies the VPD information to a controller. The panel should also be able to get rid of the waste products exuded by the plant root. An outflow is provided by the concept. The panel structure holds all the different parts interacting with each other. The 3d model exemplifing this idea can be seen in figure 3.9. Need to fit to presentation pattern.

Figure 3.8: The plant panels proposed by this work.

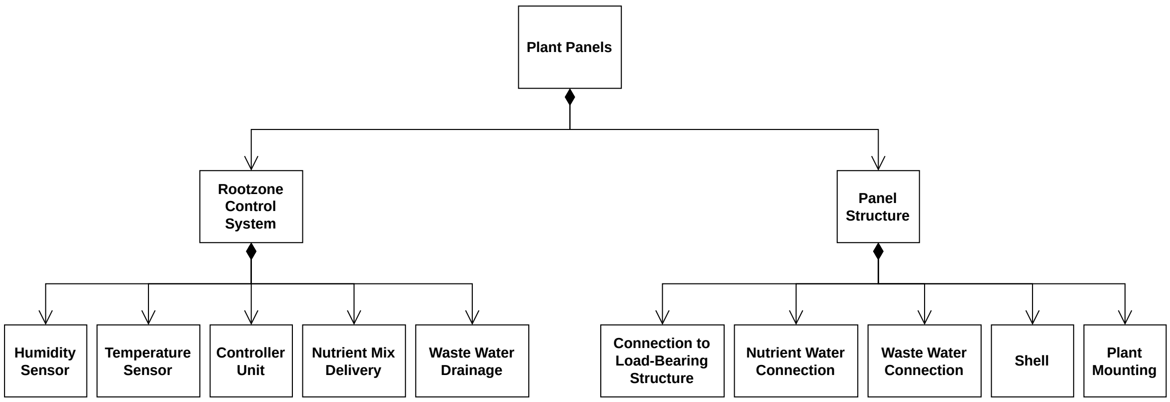
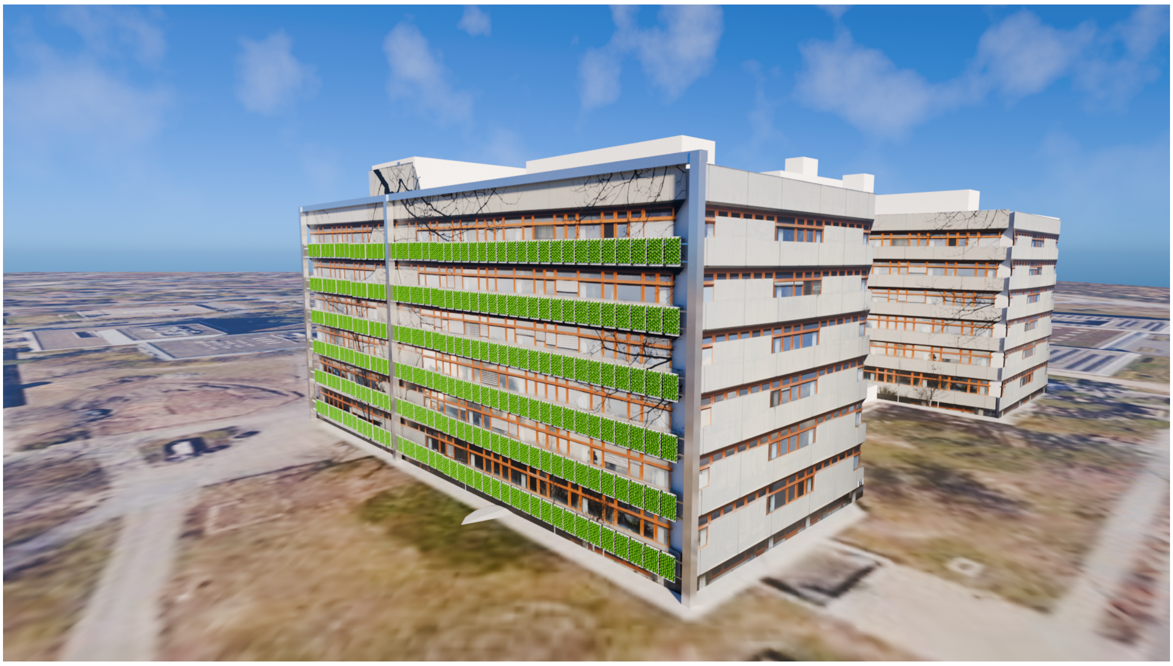


Figure 3.9: 3d model showing the plant panels mounted to the building facade.



Transportation System

As mentioned before the system needs to transport the panels to and from the facade. This is again a supporting function not found in the main system description. The system needs to mount and demount the panels to and from the load bearing structure (3.6). Then it needs to move the panels across the face of the building to a base where they can be harvested and restocked with fresh plant shoots. It should also be as low profile as possible. From this the concept of a wire-hung platform is developed. It consists of a main 'platform' responsible for (un-)loading the panels and necessary 'control'. A 'hanger assembly' made up of steel wires moves the platform. The structural architecture of the block can be seen in figure 3.10 while a closeup of the transportation system is shown in picture 3.11.

Figure 3.10: The transport platform eliminating the need for manual (de-)mounting.

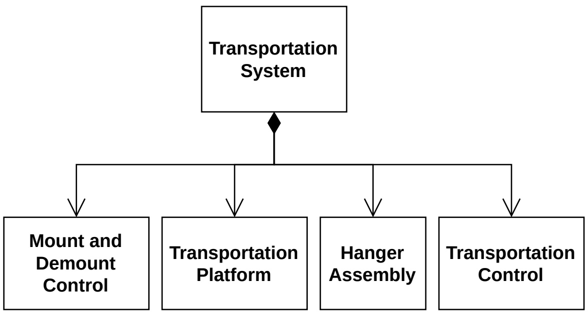
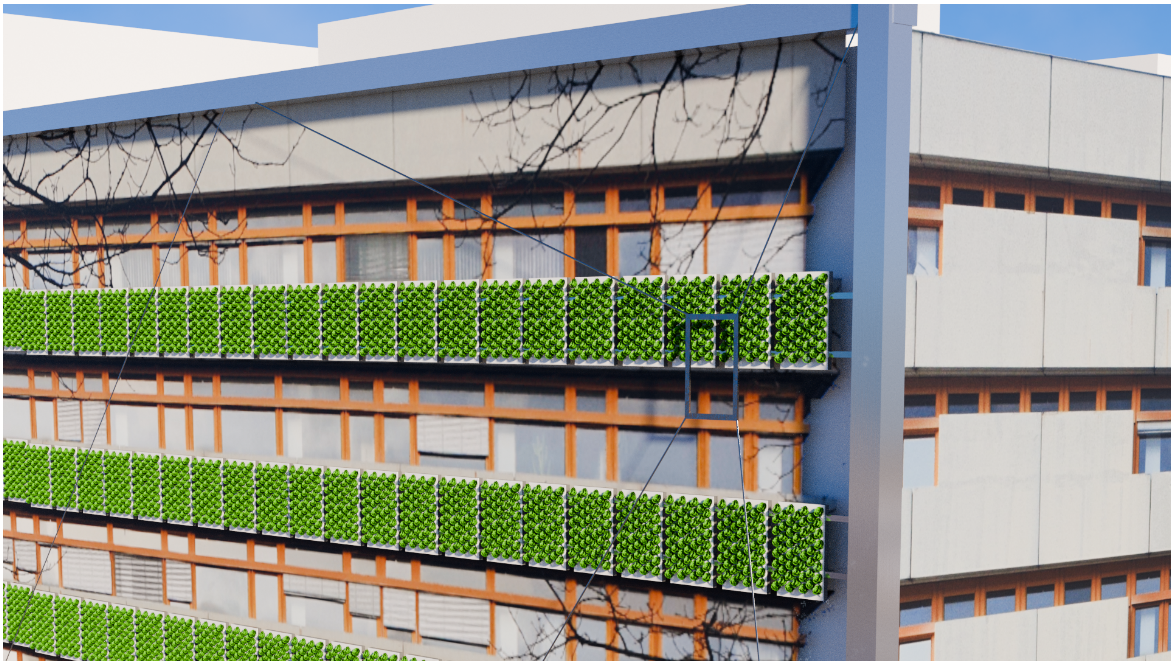


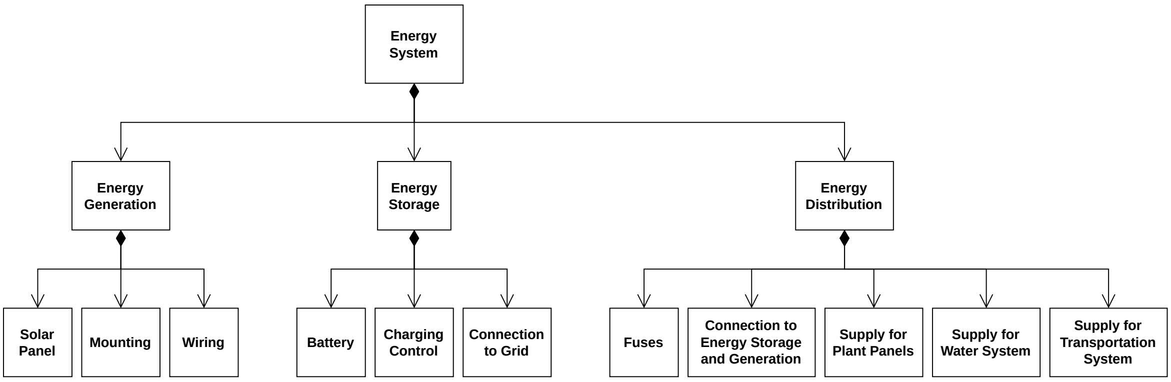
Figure 3.11: 3d model showing the general idea of the transport platform.



Energy System

Next a system needs to provide power to all the electronic subsystems. This can be expanded into energy storage and generation as well. The reason for this is to counteract the energetic impact generated by the farm as much as possible. This is done because as mentioned before, the German electricity mix is far from carbon-neutral. Consistent with our motivation to make food production more green, a solar array is considered to generate energy. As we will show later in 4 it may even be possible to completely nullify the energy consumption with this procedure. Requirements. Provide a Direct Current (DC) power circuit to all the components. The biggest consumer of power, the LEDs need DC and therefore the main circuit is chosen to be DC. This fits in well with a battery and solar array. Next the system shall generate energy by a solar array. The reasons for this are mentioned above. The chosen irrigation strategy is highly dependent on active control, otherwise the plant roots dry out quickly. So we need to store energy to be resilient to power outages. The system shall provide a connection to the grid. This is because the energy generation and consumption in our farm show a negative correlation. When the sun is shining, the Photovoltaic (PV) installation will provide a lot of energy, while not much energy is needed for supplemental lighting. Conversely, when there is little sun, we have a high energy demand from the LEDs, while not much energy is generated. Structure. So from these requirements we separate the system into the three parts ’energy generation’, ’energy storage’ and ’energy distribution’with appropriate parts in each seen in figure 3.12.

Figure 3.12: The energy subsystem.



Climate Control

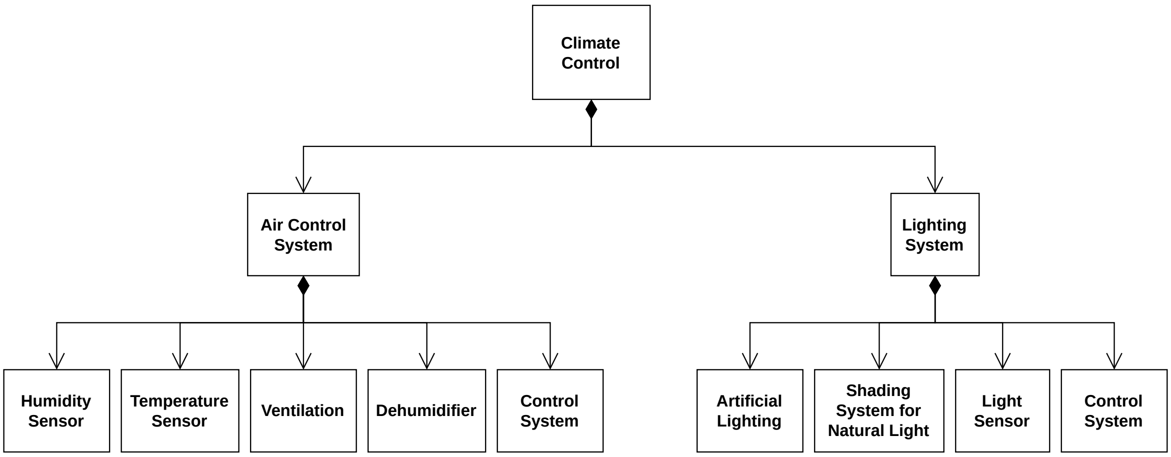
The function of optimal light and reasonable atmosphere control is compounded into one part, the climate control. Requirements and structure. The lighting system as discussed before needs to provide a structure to shade from excessive light. This is proposed to be simple semi-transparent cloth similar to existing greenhouses. It would be deployed similar to an awning to not block the view of the people inside the building. Next if there happens to be little sun, we need to supply supplemental lighting. LEDs are chosen for a few reasons. Their spectrum can be adjusted for the task of growing plants quite well. They are comparatively cheap and efficient and therefore also do not produce a high amount of excess heat. The amount of light entering the farm needs to be monitored and the shades and LEDs regulated with a control system.

For the atmosphere control we need to monitor the air volume and so sensors specified in section 3.1.2 are employed. Ventilation is required. This takes the form of a passive system in our concept. Simple windows at the top and bottom of the farm will provide airflow. They can be controlled according to the sensor inputs. What do I do with dehumidification? The internal block diagram can be seen in figure 3.13.

Envelope

The envelope provides the secondary function of separating the farm from its surroundings. This is not formulated explicitly in the functions above. Because it is inherent to have a separate environment if you would like to provide atmosphere control. Requirements and structure. As the function says the envelope needs to provide a separation

Figure 3.13: The climate control to take care of the leaf environment.



to the city environment. This is accomplished by self-supporting framing and some sort of glazing. For this work we propose glass as it is durable and visually pleasing. This is wrapped around the whole farm and building. Not a requirement for our concept but another resulting function of this structure is the insulation. One could imagine confining the envelope to the panels and therefore facade area. When just covering the facade it would be best to separate the envelope and the insulation into two distinct parts. This is because traditional insulation needs to be very close to the wall with little air movement. For this work we chose to simplify this structure and therefore just encapsulate the building in a greenhouse shell. This comes with the added benefit of insulating the window area of the building, which usually is responsible for a high fraction of the heat loss of a building. The complete architecture can be seen in figure 3.15.

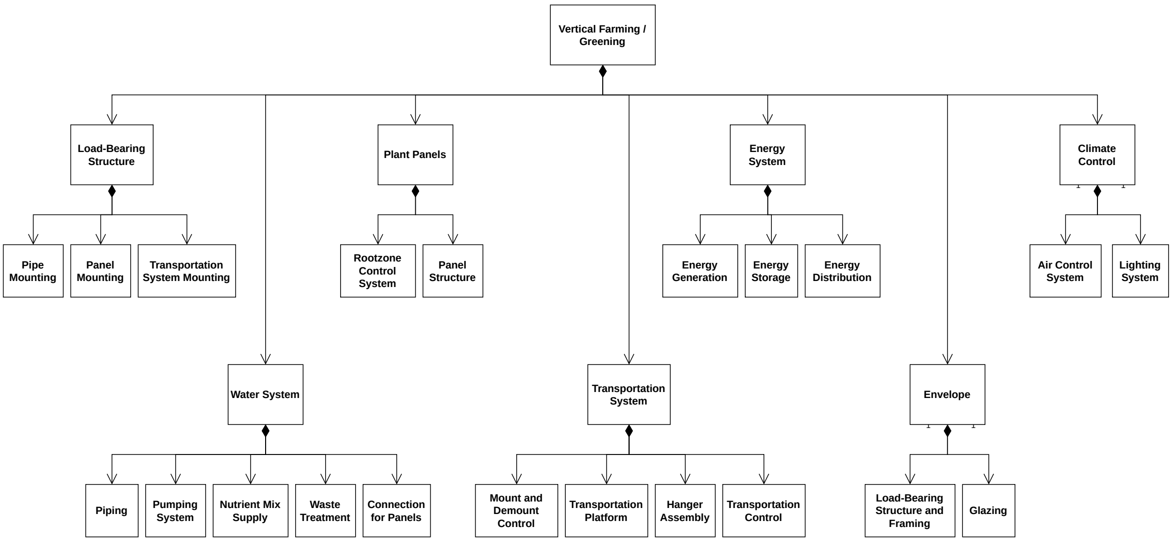
Switch climate control and envelope in full architecture.

3.3 Feasibility

Lastly to judge the proposed system a number of metrics are introduced. These serve to evaluate the feasibility of the concept. Feasibility in this work does not mean that a system like this definitely makes sense. But only to judge and evaluate the concept on a few different fronts. The metrics this work proposes, are as follows:

- The energy consumption can be met through a solar installation covering at most the area on the roof.
- Yield can offset investment costs in a reasonable timeframe.

Figure 3.15: The structural architecture of our farming concept.



- Farm provides measurable insulation increase in comparison with the 'naked' building.

- Acceptance of potential customers to put a greenhouse on the side of their buildings (not evaluated in this work)

These points will be picked up later in 5 to assess the outcomes of this work.

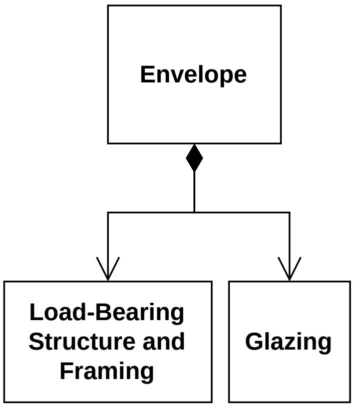
3.4 Energy System Architecture

3.4.1 Choice of Components

Shading is not considered in this work to preserve visibility from the building to the outside. And so natural radiation R_{N} shines unimpeded onto the plant. Considering the importance of illumination to the growth of the plant however, this might need be revisited in future works.

Trace substance.

Figure 3.14: The envelope segregating the farm from the city environment.



Chapter 4

Showcase of Example Unit and Simulation

4.1 Introduction to the Simulation Environment

4.2 Introduction to the developed models

4.2.1 Plant Model

Evapotranspiration

References for the ET calculation:
https://etcalc.hydrotools.tech/pageMain.php
https://www.fao.org/4/X0490E/x0490e07.htm
https://www.fao.org/4/X0490E/x0490e0k.htm

Yield

An initial state had to be given for x_{nsdw} and x_{sdw} to avoid a division with zero.

4.2.2 Physical Environment Model

Need to employ shading in the simulation.

4.2.3 LED Model

4.2.4 Pump Model

4.2.5 Air Conditioning Model

Note that CO_2 concentrations are not dynamically calculated in the simulation and the humidity contribution from the plants is not considered. The reason for this, is that the air volume component allowing for dynamic calculation led to frequent convergence errors not further investigated in this work. The chosen value for CO_2 is

365 ppm, which is an average value for the atmosphere https://doi.org/10.1111/j.1365-3040.2007.01641.x. For the VPD calculation, humidity levels are taken from weather data and temperature from the farm air volume.

4.3 Simulation Architecture

Buildings.ThermalZones.ReducedOrder.RC.TwoElements for Radiation modelling

4.4 Analysis of Energy Use and Comparison with State of the Art

4.5 Results

Insulation performance – calculate average insulation value for the colder months.

Chapter 5

Results

Chapter 6

Discussion

Chapter 7

Conclusion and Outlook

Shading is not considered in this work to preserve visibility from the building to the outside. Include CO2 and humidity in simulation.

Feasibility of aeroponic system with piezoelectric vaporizer in a long term deployment. Also, the nutrient density of the fog changes due to the vaporization. Would be interesting to design an experiment mixing specific nutrient solution, then vaporizing, then condensing and analyzing how it changed. This has not been done before as far as the author can tell.

List of Figures

List of Tables