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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

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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

HVAC Heating, Ventilation and Air Conditioning

LED Light Emitting Diode

KISS Keep It Simple, Stupid

ibd internal block diagram

EC Electrical Conductivity

AC Alternating Current

DC Direct Current

PV Photovoltaic

HV High Voltage

LV Low Voltage

BLDC Brushless DC

CC Constant Current

TMY Typical Meteorological Year

ODE Ordinary Differential Equation

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 main objective 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 for reasons which are discussed in Section 3.1.

To accomplish this goal, first the Fundamentals introduce 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 the Theoretical Analysis and Approach, 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, this paper suggests using the basement for farming. A space which is currently already in use for most buildings. Coming back to this work, in section 3.2.2 the general architecture of the system is constructed and visualized with SysML diagrams. The concept of the plant panel is introduced. This presents an idea on which much of the concept hinges. The vision of the architecture is shown via Blender models representing a tangible implementation at Friedrich-Alexander-University. A more concrete power system is developed in section 3.2.3 and components are picked to actualize the aforementioned realization. This will later guide the models developed for the simulation. Section 3.3 stipulates requirements to judge feasibility of the present retrofit concept. Also, metrics to evaluate these requirements are discussed. 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. Mathematical models describing water use and yield output for the crop 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 transformation, 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

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

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 ($\frac{\mathrm{W}}{\mathrm{m}^2\,\mathrm{K}}$) while the mathematical description is given by Newton's law of cooling

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

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

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

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

where T (K) is the material temperature, σ ($\frac{\mathrm{W}}{\mathrm{m}^2\,\mathrm{K}^4}$) 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 $\dot{Q}_{\text{inci}}$ (W) to obtain

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

for captured heat flux by a material.

2.1.3 Other relevant thermodynamic properties

Heat Capacity.
Heat transfer via mass transfer.
$Vab, p = CDwh(2/\rho 0)0.5\Delta pm$, Buildings.Airflow.Multizone.DoorOpen Pressure difference by stack effect.

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 in an artificial setting? 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

For the application at hand, the instantaneous radiation can further be divided into light spectrum and intensity. The two concepts Photosynthetically Active Radiation (PAR) and Photosynthetic Photon Flux Density (PPFD) quantify these qualities for natural and artificial sources respectively and will be introduced in this section.

Light Intensity Natural light and how to calculate the intensity on a tilted surface. Surface tilt and azimuth. Add tmy?

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 $\frac{\mathrm{W}}{\mathrm{m}^2}$ to PAR ($\frac{\mathrm{\mu mol}}{\mathrm{m}^2\,\mathrm{s}}$) @reis2020.

For artificial radiation a light source with specific spectrum characteristics can be chosen. Targeting the peaks of photosynthetic activity. This used to be more constrained in the past. But the proliferation of LEDs allows for fine-grained adjustments of light quality. For these artificial sources the concept of PPFD ($\frac{\mathrm{\mu mol}}{\mathrm{m^2\,s}}$) in analogy to PAR is usually applied. They both carry the same unit and except for their origin, can be treated the same. As such, if the source does not matter, the names will be used interchangeably in this work. A certain amount of PPFD / PAR is optimal for the plant. This however, depends on a myriad of other factors like plant species, temperature and CO_2 concentration.

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.

Time Aggregation

When PPFD and PAR are applied over a period of time, there are some considerations to be made. A pure mechanistic understanding would suggest that more light always results in more photosynthesis. This however is not the case. The plant actually performs better when periods of darkness are introduced. This dark period is a parameter of CEA systems and makes sense when viewing the plant as a form of life, requiring time to rest.

During intervals of light exposure the total accumulation of radiation is captured by the concept of Daily Light Integral (DLI) ($\frac{\mathrm{mol}}{\mathrm{m^2\,d}}$). This assimilates the instantaneous PPFD to quantify an optimal value for different plant species. For constant artificial sources this can be calculated as

$$\mathrm{DLI} = \frac{86400}{1000} * \mathrm{PPFD}$$

converting µmol to mol and accumulating the 86400 seconds contained in one whole day. With varying radiation the integral

$$\mathrm{DLI} = \int_0^{86400} \mathrm{PAR}(t)\ \mathrm{d}t$$

is taken.

2.2.2 Irrigation

Water and Nutrients in CEA are mixed and delivered to the plants directly by a process known as fertigation. The most important macronutrients are nitrogen, phosphorus and potassium. This mix is monitored by Electrical Conductivity (EC) and pH probes. They provide a good estimation of the solution ratios, as a full analysis would take mass spectrometry or similar technology. Not feasible in production environments. 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 other hydroponic methods. Disease and aeration. In case of water-submerged roots, one sick plant can easily infect the whole system through the circulating nutrient solution. This makes sterilization necessary to guard the crops. However, any plant before this processing step will still get infected. Oftentimes there is only one sterilization stage for the whole hydroponic circuit. 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.

2.2.3 Atmosphere

As elaborated before, CEA aims to optimize photosynthesis. The chemical input from the atmosphere is CO_2. Supplying this molecule is straight forward as air already contains carbon dioxide. The availability to the plant can be enhanced by elevating the concentration in the leaf environment. This is routinely done to increase yields in greenhouse and CEA settings.

Next to the pure abstraction of photosynthesis, the plant needs some other factors to thrive. The air temperature is required to stay in a certain range to sustain the crops' life. The optimal value is dependent mostly on the species. Next water in the form of humidity is also relevant for atmospheric control. That is because 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) (kPa). This describes both temperature and humidity of the air. 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 at the given temperature and transpiration is also impeded. As is a pattern in these CEA fundamentals, the ideal value depends on multiple factors like the chosen crop and its growth state.

Another technological system employed in atmosphere control is ventilation. This is captured by the property of air speed and mostly is important to plant health rather than photosynthesis. The finesse of these control mechanisms has a wide bandwidth and ranges from simple windows in greenhouses to fully fledged Heating, Ventilation and Air Conditioning (HVAC) and dehumidification units supervising every aspect of the atmosphere.

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 prune the system description to our specific application. And then sculpt the concept. It also prepares us for the simulation brought fourth in chapter 4.

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. Tough there are still additional 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.

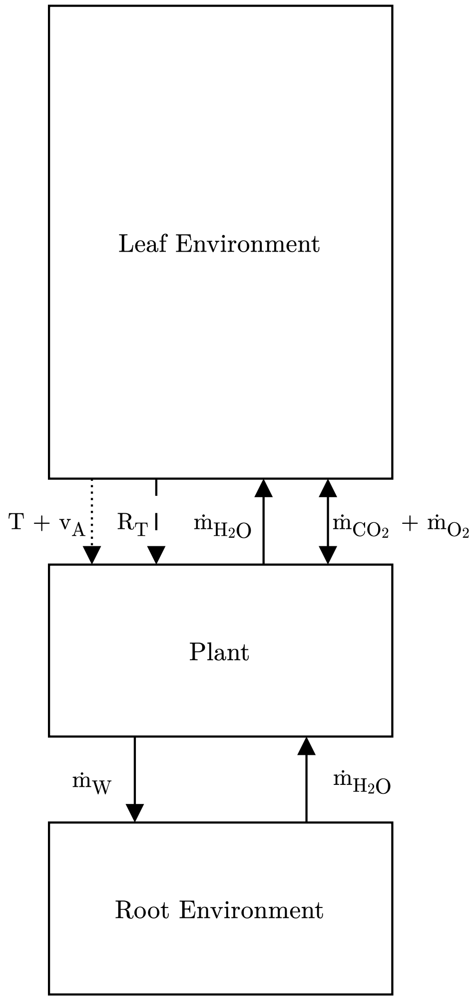


Figure 3.1: The plant and its immediate environment.

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. Any technological light source can not be 100 % efficient, and consequently heat flow from losses is modeled with $\dot{Q}_R$. 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. The mass flows $\dot{m}_{\mathrm{H_2O}}$, $\dot{m}_{\mathrm{CO_2}}$ and $\dot{m}_{\mathrm{O_2}}$ 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. Furthermore, air temperature is one of the important factors in the yield calculation later. Thus, the atmosphere management needs to be able to govern heat flow to and from the environment with $\dot{Q}_{\mathrm{A}}$. As always in control systems 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}.

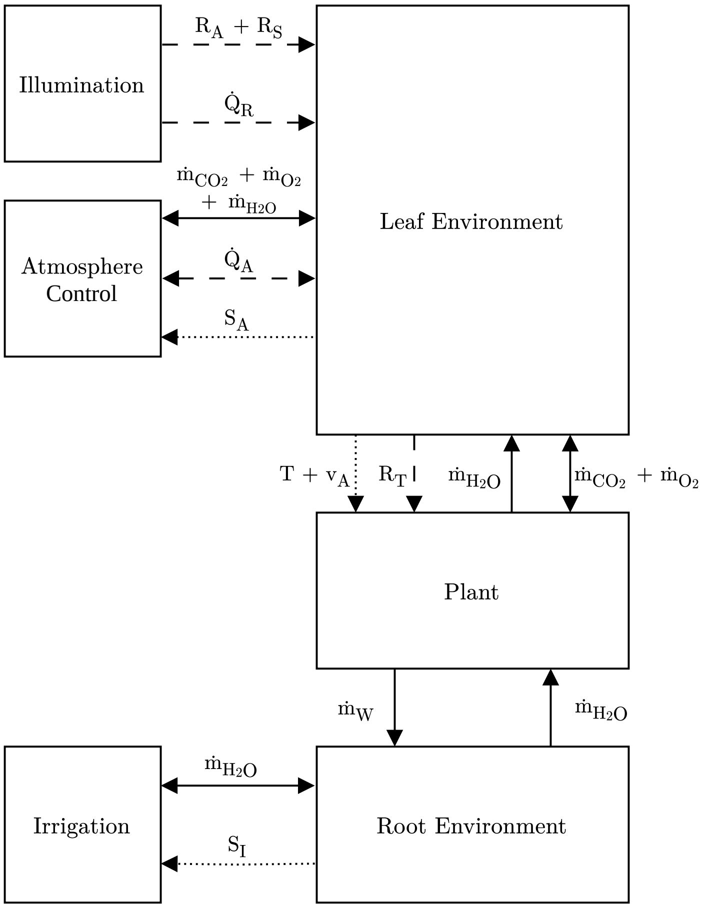


Figure 3.2: The technical system and its influences.

For irrigation, we describe the water flow with any dissolved materials as $\dot{m}_{\mathrm{H_2O}}$. 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 plant and its surroundings. Subsequently, the next section introduces the setting in which this farm 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 city $\dot{Q}_{\mathrm{FC}}$ 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 $\dot{Q}_{\mathrm{FC}}$ 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 3.5. 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

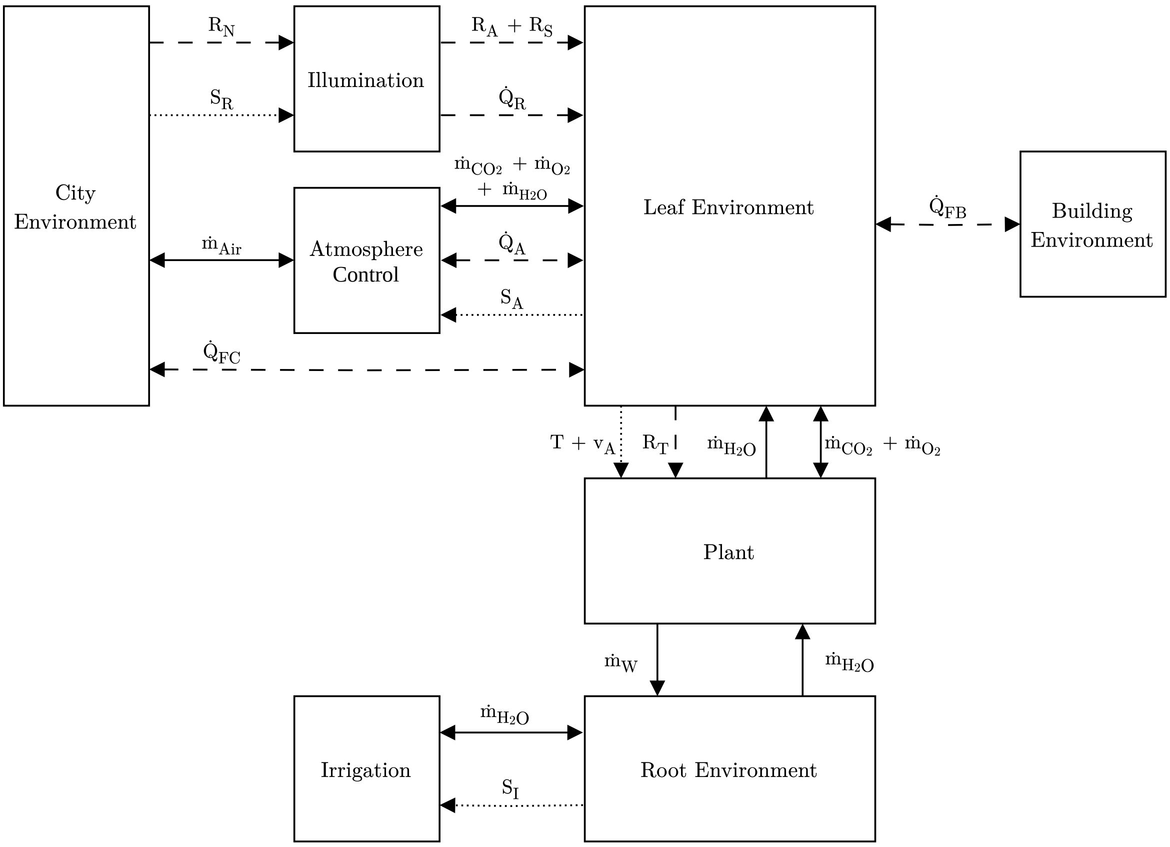


Figure 3.3: System partitioning and important flows.

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 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 the analysis lays the foundation for 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 of plant care deemed less important.

These are only a few examples, but they represent a general trend in this field. Two lessons can be drawn from these economic field studies. 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**. This is the most important result of our investigation and constitutes the research objective for this work. 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 than lettuce 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. Nevertheless clear patterns and trends are visible.

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

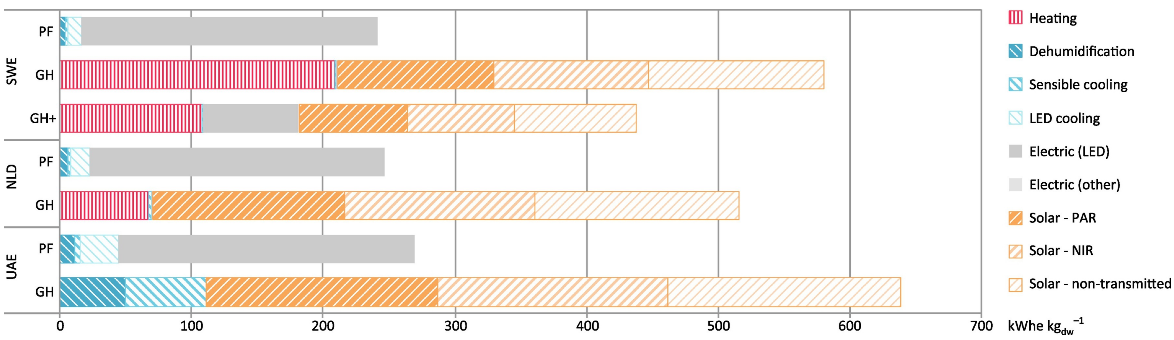


Figure 3.4: Energy use per kg dry matter in different climate conditions @graamans2018.

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, irrigation is assumed to be inconsequential for energy demand.

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

This section is still in construction.

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.

To get a rough understanding which are the most prevalent factors to influence plant growth, we will analyze a prominent lettuce yield model. Its details are introduced in Showcase of Example Unit and Simulation, for now only the inputs are examined. These are PAR, CO_2 concentration and air temperature and are taken to be the most influential factors in determining growth. Of course other factors like air flow and humidity are also essential to the health of the crop. These are however assumed to stay in a reasonable range due to natural air exchange. Just like in existing greenhouses.

A model can take the analysis only so far however. If the temperature is $-10\,°C$ for example, lettuce will die. The model happily will produce an output albeit very small. In real life, lettuce grows comfortably in the range of 7 to 24 °C and can survive temperatures even a little below freezing as anecdotal evidence suggests check again. A temperature our system can provide as shown later in Showcase of Example Unit and Simulation. Test model at -10C.

3.1.4 Conclusions from the analysis

The energy analysis showed that we need to focus on lighting to minimize energy consumption. As a result the suns' energy will be utilized. From the yield analysis we gathered that the radiation has the biggest impact on yield. Lighting thus is again the focus for our inquiry. From this follows that the illumination system should supply the optimal PPFD and accumulated DLI to the plant. In the contrary it means that the atmosphere control will be significantly cut in its competence. The ability to precisely control CO_2 and humidity is not examined in this work. This also makes sense from an economic standpoint as HVAC systems are quite costly.

From these conclusions, a new system description specifically for our implementation is presented in figure 3.5. It is slightly different to the system design proposed before. But more relevant to the concrete application in this work following the results of the analysis. The atmosphere control will no longer distinguish between mass flows of different molecules. Instead, we accumulate them together to the mass flow $\dot{m}_{\mathrm{Air}}$. We also do not consider control for the air temperature, thus the heat flow is removed from the atmosphere control.

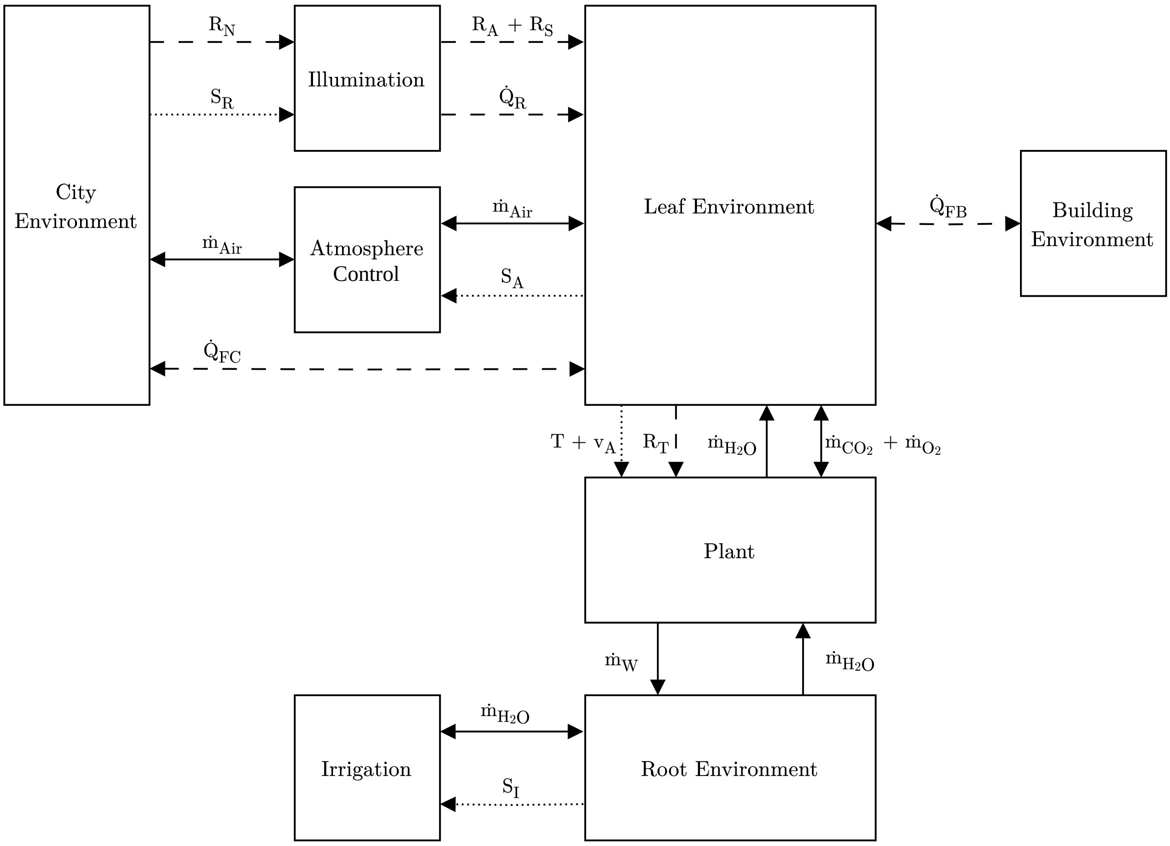


Figure 3.5: The full control system description specialized to the application.

3.2 General Concept

From the system definition (3.5), we have a clear picture on the electrical and control systems necessary. However, there exists quite a bit of engineering and logistics necessary so support this function. These will be specified in the next section. A general architecture of the system is presented which incorporates the results already established. Then a concrete implementation path for the power system is presented to go off of for our specific example unit and simulation.

3.2.1 Functional Approach

For a complete realization there exist secondary functions which need to be fulfilled additionally to the main control. For example an atmosphere management hardly makes any sense when there is no envelope to keep air in a separate control volume. Additionally, we need to supply energy to the systems and provide a structure to mount the farm to a building. From the chosen crop – lettuce – there also follows a high turnover rate. It is usually ready to harvest in four to six weeks. Therefore, easy mount and demount of the planting arrays is necessary. These supporting components to the system as well as the tasks of the main system will be formalized and presented as functions. A precise formulation of these will aid in defining our scope. The roles our concept shall serve are listed below. They break down the goals of minimizing energy consumption and maximizing yield as well as concretize what additional infrastructure is needed to achieve these objectives.

- 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.

Moreover, defining what is out of scope often helps to make the main requirements easier to understand. Functions which shall *not* be implemented are as follows.

- Provide optimal CO_2 concentration.
- Maintain optimal temperatures.
- Illuminate with optimal light spectrum.
- Offer optimal humidity levels.

This formalization provides a better understanding of the extent for this work. From this we will build the architecture in the next section.

3.2.2 Structural Architecture

The reason we formulate a structural architecture is to convey the general idea for our implementation. This shall serve to give the reader an understanding of all the parts required to realize the concept. To convey this type of system information SysML provides a standardized framework. It implements an informational model as well as a visual representation for systems engineering. Subsequently, it will be used to present the concept. There are different diagram types, of which only structural diagrams are employed in this work. More specifically the internal block diagram (ibd) is used. This type of diagram describes a systems constituents. These are pictured by rectangles. Connections have a diamond shape on the part which is deconstructed. The arrow points to the smaller components. For a full system design, there are a myriad of diagram types available in SysML. However, this work cannot provide a full system design and therefore only uses this one diagram type. This will enable us to describe the proposed concept.

For the structural architecture we will go off of two things we developed so far. Firstly the control system following our system definition (3.5). Secondly the functional architecture defined in the previous section. Detailing functionality of main and support systems. This distinction is a bit arbitrary but needs to be made at some cut-off point. For example the control system description could include a system for planting and harvesting, since it is technically needed to convert the plant to economic output. However, in this way the system description grows to large. And so main functions and supporting functions are distinguished. The order these components are introduced roughly follows a spatial line, starting from the building and attaching the systems outward to the city. In the final diagram (3.17) this is represented with more foundational components to the left of the figure. The introduction of these blocks will follow a particular pattern. Firstly the main function of the block is presented. Then other requirements for this system are laid out and the structure 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 to the outside, let us first get a look at the building in question. It can be seen in figure 3.6. It shows a 3d model implemented in Blender. The pictures for the building faces were made by the author. The 2d plane representing the ground 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 3.6: 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.

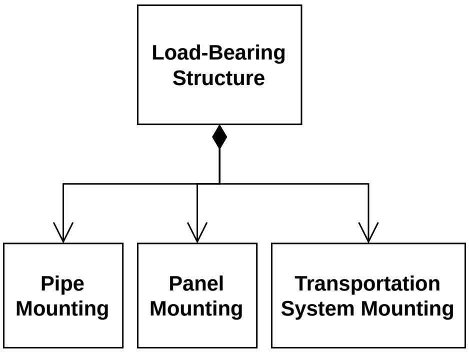


Figure 3.7: The load bearing structure.

Requirements and Structure 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. Moreover, building faces are very diverse. Consequently, the load-bearing infrastructure needs to be closely matched to the existing building. It provides the interface for other subsystems. The mounting for *Pipes*, *Panels* and *Transportation System* are part of different components and are defined later.

Water System

The next system that would need to be installed is the water system. It is not equivalent to the irrigation in our system description from 3.5. 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. Distributing the solution across the whole farm, as well as preparing it with optimal EC and pH-levels.

Requirements and Structure The water supply needs to interface to the actual irrigation system. This is illustrated by the part *Connection for Panels*. A water tank stores and supplies the *Nutrient Mix*. We later reason that the energy of the farm should be supplied by a Photovoltaic (PV) array. With this knowledge it makes sense to position the water tanks on the roof of the building. During the day solar energy can be used to pump and prepare the water mix. And during nighttime gravity will provide water pressure to the system. A connection to the water system of the building is also conceivable. This would need to process and monitor the nutrient mix either on the roof aswell – to keep the water pressure – or distributed at every floor. To keep the retrofit concept simple and minimally invasive, a separate water circuit is proposed here. To facilitate the water flow *Pipes* and a *Pumping System* is needed. Furthermore, drainage for the *Waste Products* as well as treatment is required.

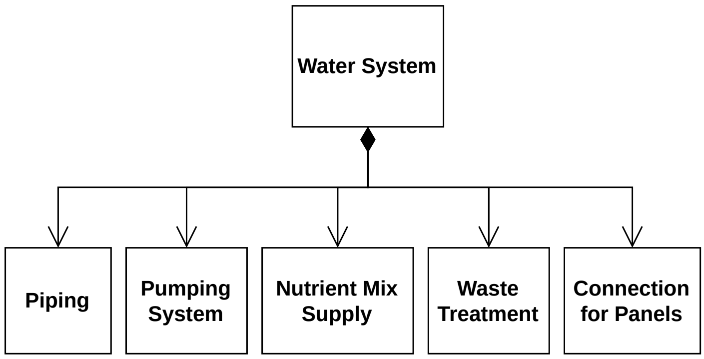
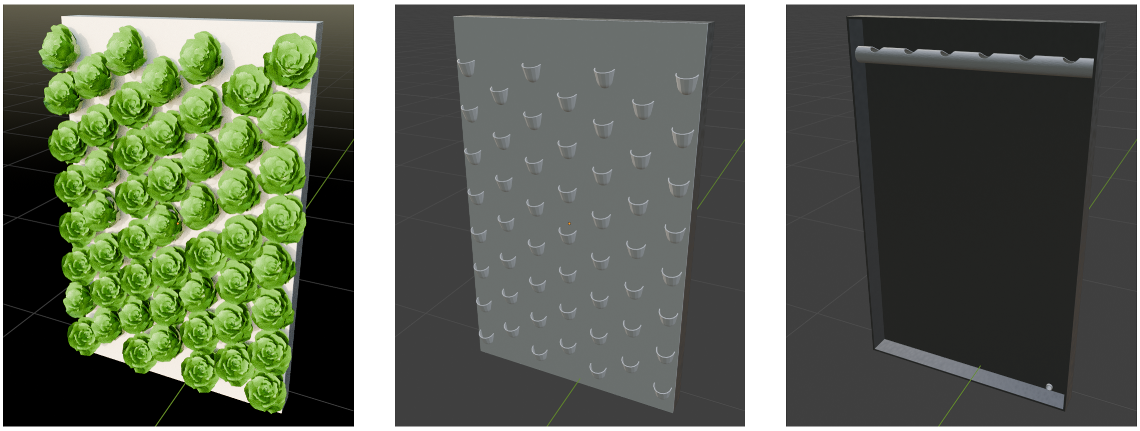


Figure 3.8: The water system mixing and delivering the nutrient mix.

Plant Panels

For the actual irrigation system we will go into a little bit more depth. The concept of the plant panel will ensure optimal water and nutrient delivery to individual plants.

Requirements and Structure The general idea is 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 to stop the spread of plant diseases. As well as provide 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. Additionally, the system needs to be slim to not require big open spaces in front of the building. With these requirements we arrive at a panel like architecture. Now that we have a rough outline of what we want the system to look like, 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 – a container segregating the root environment from the rest of the farm. 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. For the aeroponic system, an ultrasonic piezoelectric vaporizer is placed in a water-filled upper part of the panel. Which can be seen in figure 3.9 (c) illustrating the inside air volume. There, a pipe is shown to house the vaporizers. This sustains a fog which provides *Moisture and Nutrients* to 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 (3.5) 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 architecture is presented in figure 3.10. And a 3d model mounting the panels to the building can be seen in figure 3.11. Rename elements in architecture to fit with names in the text.



(a) (b) (c)

Figure 3.9: 3d models of the plant panels (a) fully stacked with lettuce, (b) empty, (c) open to expose the inside space for roots and nutrient fog.

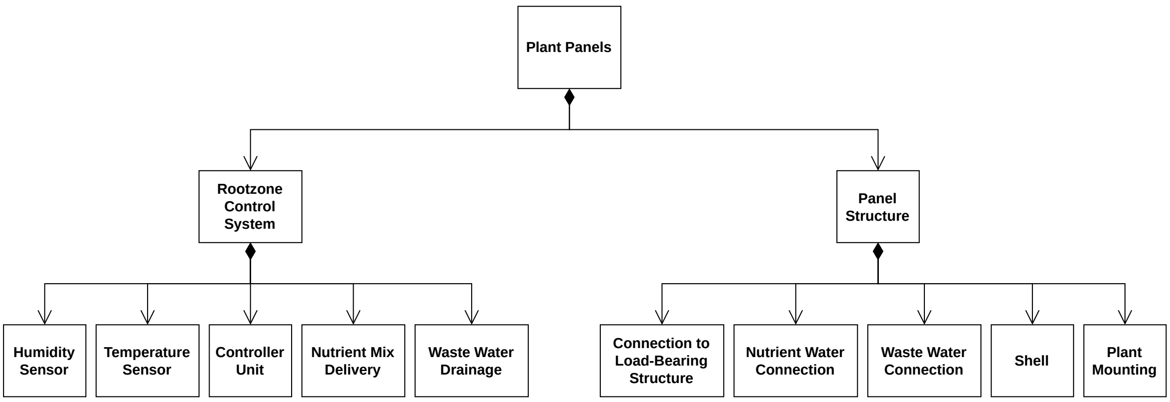


Figure 3.10: The plant panels proposed by this work.

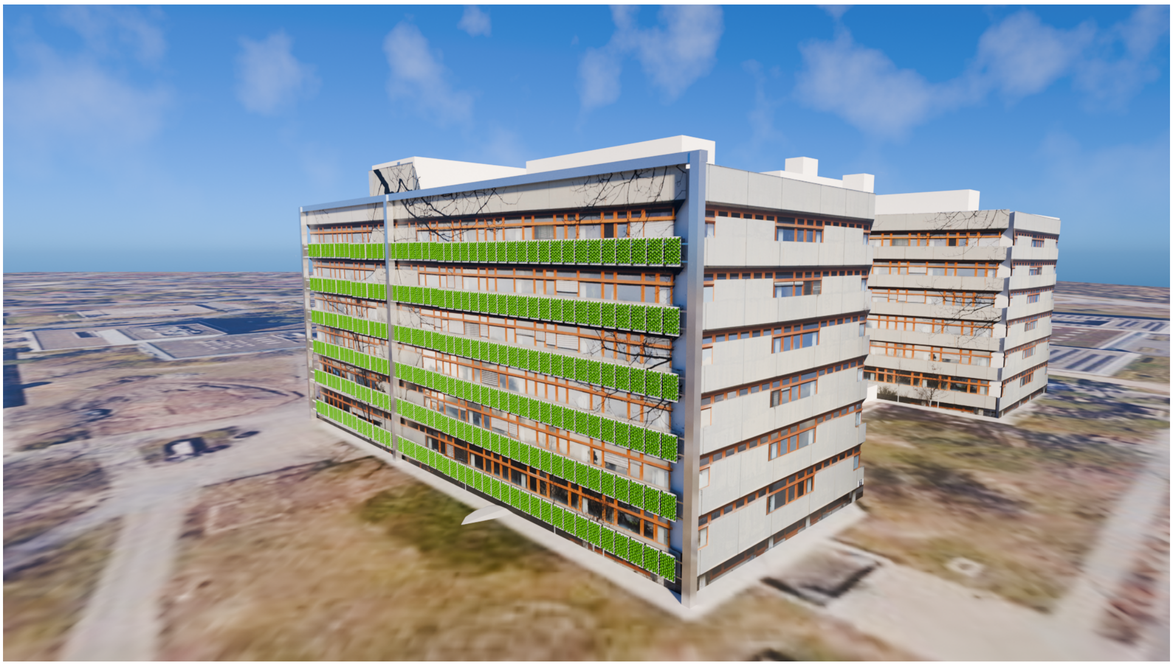


Figure 3.11: 3d model showing the plant panels mounted to the building facade.

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 control system description.

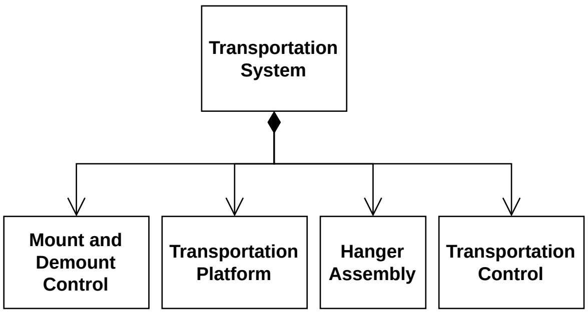


Figure 3.12: The transport platform eliminating the need for manual (de-)mounting.

Requirements and Structure The farm needs to *Mount and Demount* the panels to and from the load bearing structure (3.7). 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 structure responsible for (un-)loading the panels and necessary *Control Infrastructure*. A *Hanger Assembly* made up of steel wires supports the weight of the construction and moves it around the farm. The structural architecture of the block can be seen in figure 3.12 while a closeup of the transportation system is shown in picture 3.13.

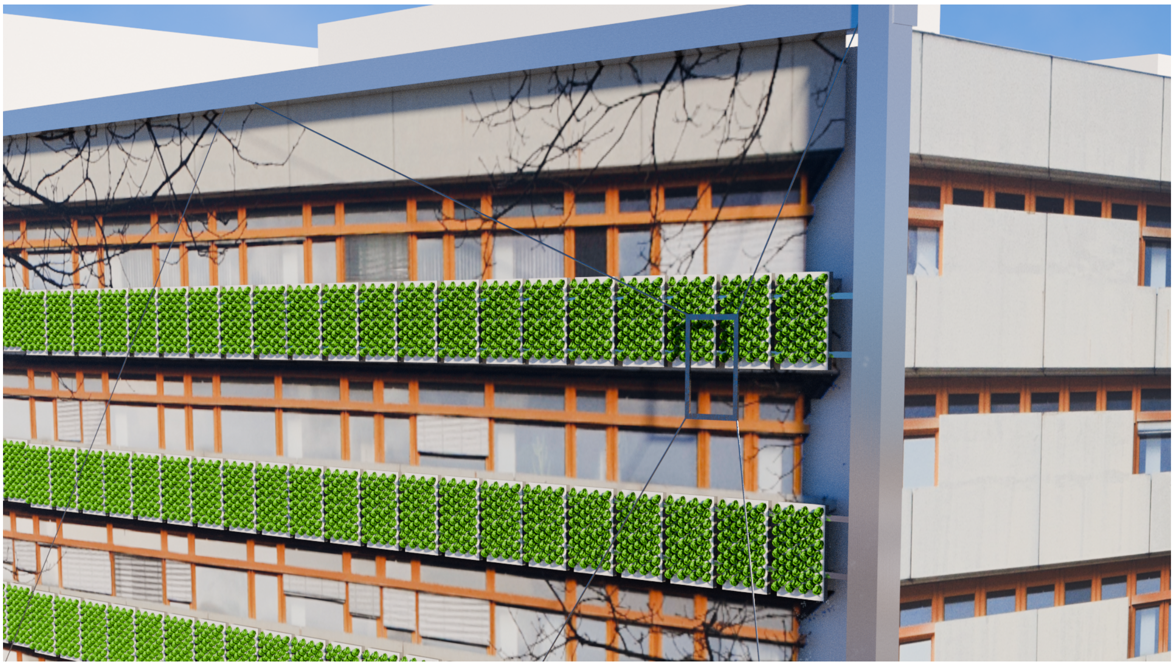


Figure 3.13: 3d model showing the general idea of the transport platform.

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 chapter 4 it may even be possible to completely nullify the energy consumption with this procedure.

Requirements and Structure As we want to employ PV it makes sense to rely on Direct Current (DC) components wherever possible. The biggest energy consumers are the lighting fixtures. LEDs are chosen for a few reasons closer illustrated in the Climate Control. They need to be supplied by Constant Current (CC) which usually is more easily converted from DC circuitry as well. 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. Hence, an energy storage is needed. Batteries are chosen for this task as they are the most comfortable way to store electrical energy. The system shall also 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 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. So from these requirements we separate the system into the three parts *Energy Generation*, *Energy Storage* and *Energy Distribution* as seen in figure 3.14.

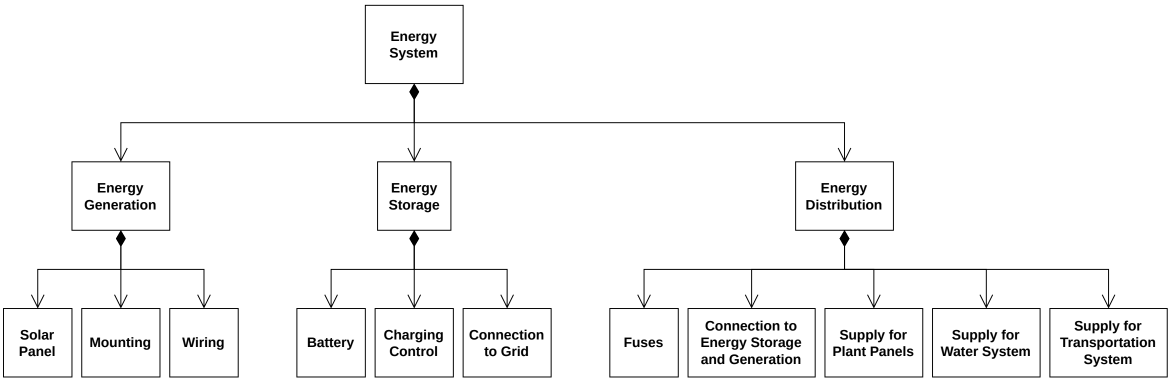


Figure 3.14: The energy subsystem.

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 comparable 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 finely adjusted to facilitate photosynthesis exceptionally well. They are comparatively cheap, efficient and therefore also do not produce a high amount of excess heat. Furthermore, they offer class leading lifespans. 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. For the architecture we also consider *Dehumidification*. As plants evaporate water the humidity inside the farm will rise above average levels. This may pose a problem for the building facade and air quality. In our later inquiry and simulation it is dropped however as atmosphere control is not the focus of this work. The internal block diagram can be seen in figure 3.15.

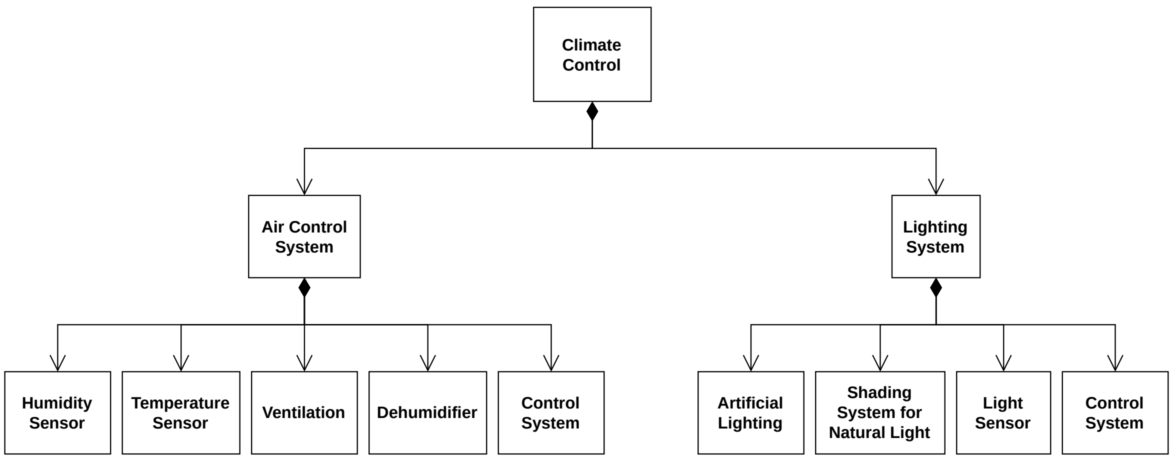


Figure 3.15: The climate control to take care of the leaf environment.

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.

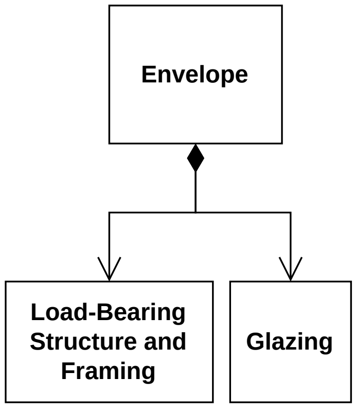


Figure 3.16: The envelope segregating the farm from the city environment.

Requirements and Structure As just discussed the envelope needs to provide a separation to the city environment. This is accomplished by *Self-Supported Framing* and *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, which usually is responsible for a high fraction of the heat loss of the building. The complete architecture can be seen in figure 3.17. Note that this diagram only goes down to the second level of block definition. This is done to make it more comprehensible. A more detailed look at the components is already provided in the sections above.Add 3d model of full farm.

Switch climate control and envelope in full architecture.

3.2.3 Power System Architecture and Choice of Components

As argued before we employ a battery and PV installation. It makes sense to rely on DC devices wherever possible. These parts will be detailed more diligently in the following part. We will go through the components in order of their electricity consumption in traditional CEA systems. Then High Voltage (HV) and Low Voltage (LV) circuits are introduced to connect the system together.

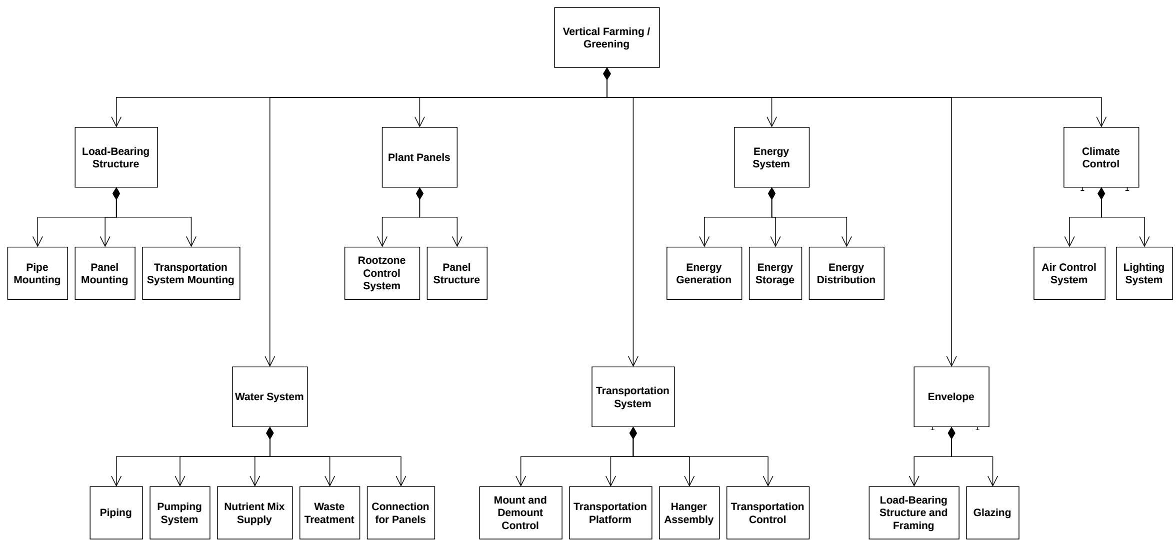


Figure 3.17: The structural architecture of our farming concept.

Illumination

For shading one could imagine two types of deployment. Linear Actuators extending the cloth of the awning or rotary motors rolling up the fabric. Because of the prevalence of ordinary rotary motors, they are chosen for this application. Now the choice presents itself if traditional DC or Brushless DC (BLDC) motors are deployed. This work chooses BLDC motors across the board for small to medium actuation tasks. They are available in a wide variety of power classes, offer high efficiency and long operational reliability. The general idea for deployment is to use one motor for multiple awnings. As speed is not of importance, we can use a transmission – of for example 1:100 – to drive all awnings on one floor. We choose the *PBL42-15 48V* motor by Parvalux. It offers a continuous torque of 0.063 N m, resulting in around 6 N m after the transmission. This work does not verify the exact value by calculation, nevertheless it should be plenty for this application. The transmission ratio can also still be changed later if not suitable. The motor requires a 48 V DC connection.

Next up we discuss the artificial lighting. There exists a very large variety of LED lighting products specifically for horticulture applications. *300 XT EVO MIXED LM301H 3500K+4000K+660nm+730nm KIT* from LED-Tech is chosen because it offers full spectrum light. This is important because we want white illumination as discussed before. The spectrum is still optimized for photosynthesis, emitting light peaks at around 440 nm and 660 nm, close to the optimal absorption wavelength of chlorophyll a & b. It uses LM301H LED diodes manufactured by Samsung which offer class leading efficiency. Additionally, LED-Tech provide great documentation showing the exact spectrum and light output for any of their LED modules and different supply currents. When driving the chosen panel at 2.1 A, it outputs 218.28 $\frac{\mu mol}{s}$. Pretty close to the PPFD of 200 $\frac{\mu mol}{m^2 s}$ which is optimal for lettuce cultivation. Did I already introduce this? So one of these panels is deployed per square meter. As introduced before LEDs need to be run with a CC source. It is proposed here to deploy one driver per LED module. This work does not go further into the topology of these circuits. Next we will talk about the actors needed for the chosen atmosphere control.

Atmosphere Control

As argued before, the atmosphere control implemented here is confined to a passive system. This is realized by opening and closing windows. Again the same BLDC motor as for actuating the awnings with a higher transmission ratio of 1:200 is chosen. A simple rack and pinion gear combination is picked to open the windows. The torque of 12 N m is supposed to be enough to drive the windows per floor. Windows are placed on the lower and uppermost floor to promote air flow. The coming section introduces the pumping system.

Water System

For the irrigation circuit we propose a BLDC with a higher power rating by Lorentz. They specialize in solar-powered pumps and are therefore perfect for our deployment. Their *PS2-4000* controller and *ECDRIVE 4000* pump combo is able to supply the needed water flow rates to the building height. As can be seen in their documentation. The required flow will be simulated later in chapter 4. The controller takes a maximum voltage input of 375 V and transforms it to three-phase 240 V Alternating Current (AC) for the motor.

PV Installation

HV and DC Circuits

The system will make use of a HV and multiple LV circuits. The HV part orients itself to be compatible with batteries of electric vehicles. Following our motivation for a more sustainable and circular economy, this opens up the possibility to reuse old car batteries. They usually provide a voltage between 350 - 400 V. The industry aims for higher voltages in the 800 V range for more luxurious vehicles. However, budget oriented options are posed to stay at the aforementioned voltages. Our chosen water pump has a maximum input voltage of 375 V and so the lower end of around 350 V is chosen for the HV circuit. For the LV part a 48 V circuit is chosen. This is a common value in LV power distribution networks. However, because we have a lot of components, the power we need to supply is high. This means we cannot simply rely on a singular LV circuit. The current would melt the wires. As argued before, the employed LED modules run at 2.1 A per square meter growing space. 37 V follow from this supply current according to the supplier website. We group them in pools of fifty panels. This results in a power draw of $50 * 2.1\,\mathrm{A} * 37\,\mathrm{V} \approx 3.9\,\mathrm{kW}$. At the 48 V LV distribution network this translates to ~81 A of current for one LV circuit, which is still manageable. As we have around $500\,\mathrm{m}^2$ of growing space, ten LV converters are needed in the system to distribute the load between them.

The block diagram for the energy architecture can be seen in 3.18. Because we have a lot of duplicated components – eg. ten LV converters, 500 LED modules – only one of these elements is shown at a time in the diagram. The others are connected in parallel.

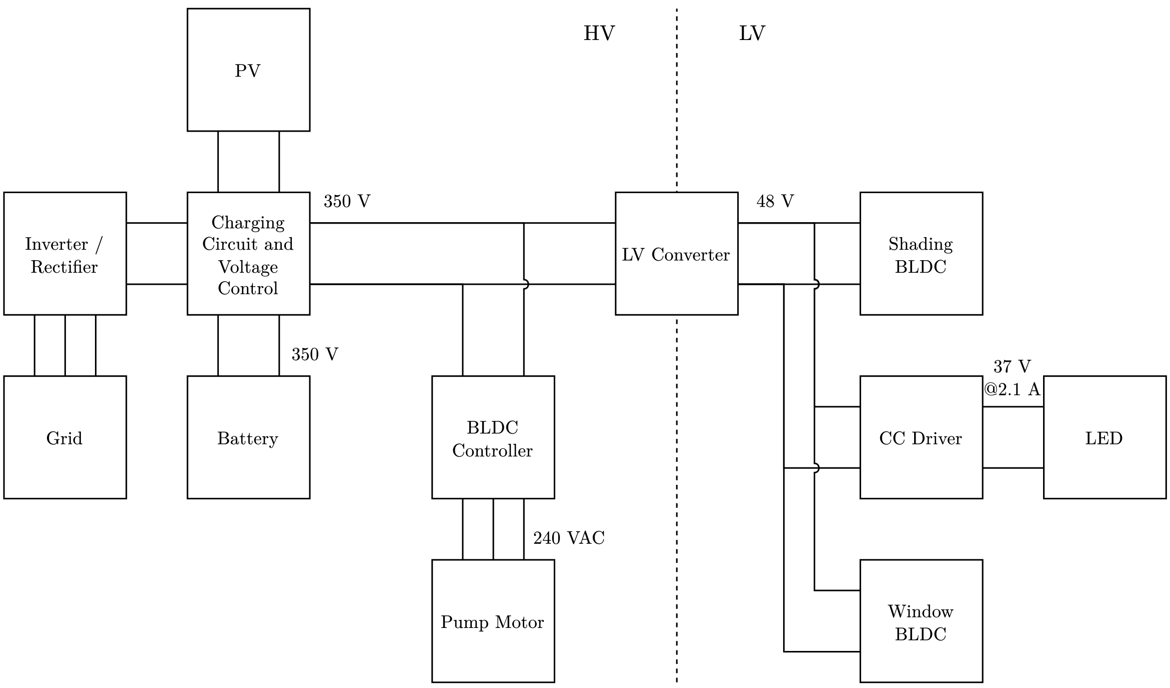


Figure 3.18: The power architecture of our concept.

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 just wants 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.
- The farm provides a measurable insulation increase in comparison with the 'naked' building.
- Acceptance of potential customers to put a greenhouse on the side of their buildings is present (not evaluated in this work).

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

Chapter 4

Showcase of Example Unit and Simulation

This chapter provides an overview over the developed simulation and what conclusions can be drawn from it. First a short reasoning for the chosen tool is given. Then we will introduce a block diagram showing the general approach to the simulation. This will make the targeted inputs and outputs apparent. Next, models implementing lettuce crop and the technical components specified in the 3.2.3 are developed. The physical environment of the farm is built up to interface with these components. A first evaluation will be drawn comparing our implementation with state of the art vertical farms.

4.1 Introduction to the Simulation Environment

First a short introduction to Modelica. The language is uniquely catered to describe multi-domain systems. This is due to its declarative nature. The equations governing the system at hand are simply written down. Causality and the progression of the variables over time is taken care of by the solver. This stands in contrast to imperative languages where a concrete sequence of steps needs to be given. Not always possible for physical systems. Matlab Simscape offers similar functionality to integrate with their Simulink program. But the available libraries are not as vast as for Modelica. For these reasons Modelica is chosen. It provides the best framework for our investigation, as our use case is a cyber-physical system. There exist a variety of GUI-Frontends to the language. OpenModelica is picked because it is an open-source project freely available.

Additionally, the Modelica Buildings Library is utilized extensively. It offers a broad range of models specifically for building design. Questions in this domain are quite similar to the ones posed in this work. Heat fluxes, solar radiation and mass flows as well as control blocks all have detailed models we can build upon.

Intro to the interfaces heat port, real input, fluid port, ...

4.2 Simulation Structure

To generate the structure we must first ask: What knowledge shall be gained by the simulation? This is a question already answered through the Feasibility requirements. The results of this chapter should enable us to make statements about *Energy Consumption*, *Insulation Potential* and *Crop Yield*. So these are the outputs the simulation shall generate. Customer acceptance is not part of the technical system and thus not evaluated. For inputs, we must discern between dynamic and static. Static data is explained closer in Section 4.3.

Dynamic inputs are the beginning to the simulation flow. Looking at Figure 3.5, any dynamic variable not generated by the farm itself must come from the context. First the building environment is analyzed. The property of interest here is the heat flow $\dot{Q}_{\mathrm{FB}}$. Following the equations from the introduction of Heat Transfer, it is calculated with conduction and convection. As elaborated before radiative heat transfer is investigated separately. Forced convection is also not applicable here, since there is very little air movement inside buildings. As a result the only relevant variable is the temperature difference. Unfortunately for this study there was no data on the building air temperature to simulate this dynamically. Consequently, it is assumed to be fixed at 20 °C – normal room temperature.

Next the city environment is broken down. The natural radiation R_{N} is the first dynamic input to the simulation. Secondly the mass flow $\dot{m}_{\mathrm{Air}}$ is dependent upon air temperature and pressure following the equation in the fundamentals (2.1.3). Thirdly heat flow $\dot{Q}_{\mathrm{FC}}$ depends again on temperature difference. Now forced convection is also taken into account since there is fluid movement in the city environment. This comes in the form of wind direction and speed. These values can all be obtained with weather data records for a Typical Meteorological Year (TMY).

From this, the general simulation flow is developed and shown in Figure 4.1. The left shows the inputs from the weather data. These are logically grouped into 'Light' for the radiation and 'Air' containing the remainder of the attributes like temperature and wind speed. Then inside the farm, temperature of the leaf environment is separated out. The controlled and engineered system are connected together according to our system definition (3.5). However not all properties shown there need to be evaluated to generate the targeted output. As shown later in the specific model description only a subset – shown in the Illustration – is implemented in the simulation. The outputs needed to judge feasibility are shown to the right. The icons used in the diagram are freely available from Google Fonts. They are also used in the simulation. Envelope is integrated in atmosphere control. Same convention as 3.5 regarding mass, energy and informational flows. Note that the temperature flow to the plant is informational. This is no mistake since there is no heat exchange, but only import to the model.

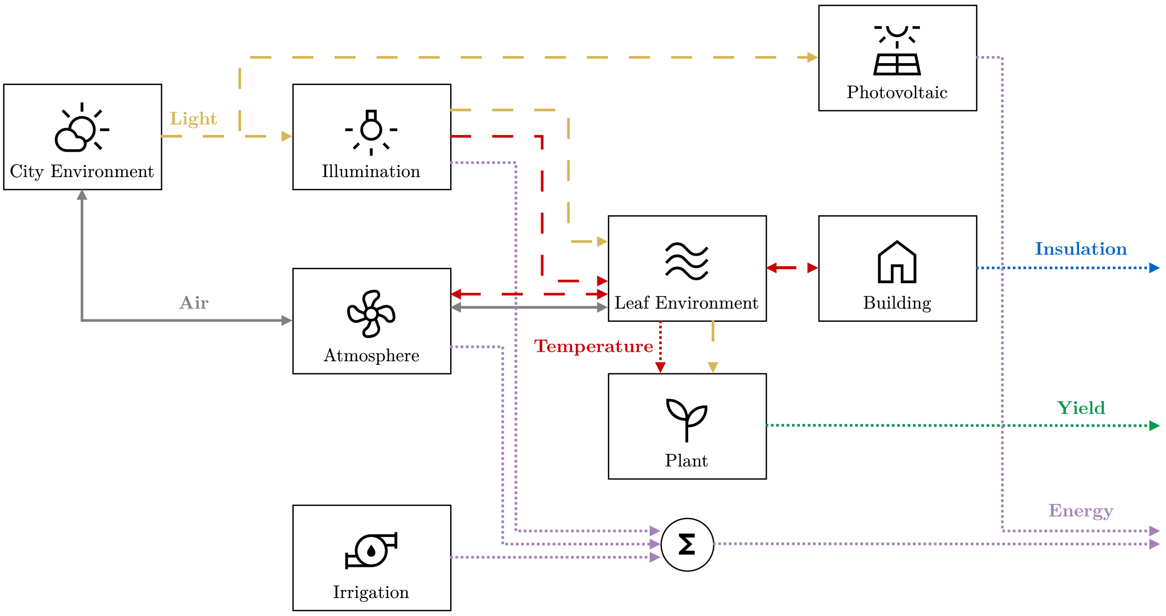


Figure 4.1: The simulation architecture implemented to assess the feasibility requirements.

4.3 Introduction to the Developed Models

List static variables?

Modelica is object-oriented, which enables the construction of a general model with parameters. These are then instantiated and the specific values for different entities can be put in. Examples for our application include the orientation of the building walls or the optimal DLI for the chosen crop. The static inputs of each model will be listed in their presentation in Section 4.3. Capitalize Figure, Section and so on in the rest of the thesis. Introduce that there are four farms.

The introduction of the models follows a pattern. First the models and their static parameters are established and then the dynamic inputs and outputs are listed.

We follow the same order as introduced in the 3.1 first describing the plant and its environments, then the engineered systems and lastly implementing the context.

4.3.1 Plant Model

Yield

The yield model employed in this study is a system of two Ordinary Differential Equations (ODEs). It was developed by @van_henten1994 and uses dry weight to assess the growth of lettuce. For this, mass is split up into the state variables structural dry weight x_{sdw} ($\frac{\mathrm{g}}{\mathrm{m}^2}$) and non-structural dry weight x_{nsdw} ($\frac{\mathrm{g}}{\mathrm{m}^2}$). The development of these two state variables over time is given by

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

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.

Which themselves are given by

$$r_{\mathrm{gr}} = c_{\mathrm{gr,max}} \frac{x_{\mathrm{nsdw}}}{c_\gamma x_{\mathrm{sdw}} + x_{\mathrm{nsdw}}} {c_{\mathrm{Q10,gr}}}^{(u_{\mathrm{T}}-20)/10}$$

$$\begin{aligned}
f_{\mathrm{resp}} &= (c_{\mathrm{resp,sht}}(1-c_\tau)x_{\mathrm{sdw}} + c_{\mathrm{resp,rt}} c_\tau x_{\mathrm{sdw}}) {c_{\mathrm{Q10,resp}}}^{(u_{\mathrm{T}}-25)/10} \\
f_{\mathrm{phot}} &= (1-\exp(-c_{\mathrm{K}} c_{\mathrm{lar}} (1-c_\tau) x_{\mathrm{sdw}})) f_{\mathrm{phot,max}}
\end{aligned}$$

with $c_{\mathrm{gr,max}}$, c_γ, $c_{\mathrm{Q10,gr}}$, $c_{\mathrm{resp,sht}}$, c_τ, $c_{\mathrm{resp,rt}}$, $c_{\mathrm{Q10,resp}}$, c_{K} and c_{lar} all being constants specific to lettuce. A clear overview over these static values and their biological meaning can be found in @abedi2023 or in the original paper @van_henten1994. The air temperature u_{T} (°C) is the first dynamic input to this model.

Next the gross carbon dioxide assimilation rate $f_{\mathrm{phot,max}}$ ($\frac{\mathrm{g}}{\mathrm{m}^2\,\mathrm{s}}$) can be calculated with

$$
\begin{aligned}
f_{\text{phot,max}} &= \frac{\epsilon u_{\text{par}} g_{\text{CO}_2} c_\omega (u_{\text{CO}_2} - \Gamma)}{\epsilon u_{\text{par}} + g_{\text{CO}_2} c_\omega (u_{\text{CO}_2} - \Gamma)} \\
\epsilon &= c_\epsilon \frac{u_{\text{CO}_2} - \Gamma}{u_{\text{CO}_2} + 2\Gamma} \\
\Gamma &= c_\Gamma {c_{\text{Q10},\Gamma}}^{(u_\text{T} - 20)/10} \\
g_{\text{CO}_2} &= \left(\frac{1}{g_{\text{bnd}}} + \frac{1}{g_{\text{stm}}} + \frac{1}{g_{\text{car}}} \right)^{-1} \\
g_{\text{car}} &= -1.32 \cdot 10^{-5} \frac{\text{m}}{\text{s}\,{}^\circ\text{C}^2} {u_\text{T}}^2 + 5.94 \cdot 10^{-4} \frac{\text{m}}{\text{s}\,{}^\circ\text{C}} u_\text{T} - 2.64 \cdot 10^{-3} \frac{\text{m}}{\text{s}}
\end{aligned}
$$

where c_ω, c_ϵ, c_Γ, $c_{\text{Q10},\Gamma}$, g_{bnd} and g_{stm} again are constant coefficients. Interesting for us are the two other dynamic inputs, the incident PAR u_{par} $(\frac{\text{W}}{\text{m}^2})$ and the CO_2 concentration u_{CO_2} (ppm). These calculations are implemented into a Modelica model as can be seen in Listing 4.1.

Listing 4.1: Modelica model for lettuce yields per m^2

```
model plant_yield
  /*
    input, output and variable definition skipped for readability
  */

initial equation
  x_nsdw = x_nsdw_start;
  x_sdw = x_sdw_start;

equation
  when reset then
    reinit(x_nsdw, x_nsdw_start);
    reinit(x_sdw, x_sdw_start);
  end when;

  der(x_nsdw) = c_alpha*f_phot - r_gr*x_sdw - f_resp - ((1 - c_beta)/
      c_beta)*r_gr*x_sdw;
  der(x_sdw) = r_gr*x_sdw;

  r_gr = c_gr_max*(x_nsdw/(c_gamma*x_sdw + x_nsdw))*c_q_10_gr^(((
      air_temperature - 273.15) - 20)/10);
  f_resp = (c_resp_sht*(1 - c_tau)*x_sdw + c_resp_rt*c_tau*x_sdw)*
      c_q_10_resp^(((air_temperature - 273.15) - 25)/10);
  f_phot = (1 - exp(-c_k*c_lar*(1 - c_tau)*x_sdw))*f_phot_max;

  f_phot_max = (epsilon*par*g_co2*c_omega*(co2_concentration -
      capital_gamma))/(epsilon*par + g_co2*c_omega*(co2_concentration -
```

```
       capital_gamma));
24   capital_gamma = c_cap_gamma*c_q_10_cap_gamma^(((air_temperature -
       273.15) - 20)/10);
25   epsilon = c_epsilon*(co2_concentration - capital_gamma)/(
       co2_concentration + 2*capital_gamma);
26   g_co2 = 1/((1/g_bnd) + (1/g_stm) + (1/g_car));
27   g_car = max(-1.32e-5*(air_temperature - 273.15)^2 + 5.94e-4*(
       air_temperature - 273.15) - 2.64e-3, Modelica.Constants.small);
28
29   dw = a_plant*(x_nsdw + x_sdw) / 1000;
30 end plant_yield;
```

There are some notable differences to the original equations. Temperature in Modelica is given in Kelvin and thus u_T needs to be converted before it can be used in the calculation. A reset is implemented in lines 11 to 14 to simulate a harvest. After which the state variables are reinitialized with their start values. This initial condition was matched to the original paper specifying 75 % structural and 25 % non-structural weight for the planting stage. Their total dry weight for the young plants ranged from 0.72 to 2.7 $\frac{\mathrm{g}}{\mathrm{m}^2}$ for greenhouse cultivation. The upper end of this spectrum is implemented in the model since hydroponic cultivation allows for high plant densities. Another difference is that the irradiance u_{par} is going into the equation with the unit $\frac{\mathrm{W}}{\mathrm{m}^2}$. So the total PAR in $\frac{\mathrm{\mu mol}}{\mathrm{m}^2\,\mathrm{s}}$ is divided by the conversion factor 4.56 $\frac{\mathrm{\mu mol}}{\mathrm{W\,s}}$ to get the equivalent value in $\frac{\mathrm{W}}{\mathrm{m}^2}$ @reis2020. The equation for g_{car} is a quadratic polynomial with roots at 5 °C and 40 °C. To avoid a division by zero it is wrapped in the `max()` function and compared with `Modelica.Constants.small`.

The model implementation was validated following a similar setup as the original paper. Their input data was not available, but was approximated with similar weather data from Germany. This resulted in an output close to the one observed in @van_henten1994.

From the two ODEs we can extract the *Dynamic Inputs*. These are the air temperature T, the PAR R_T and the carbon dioxide concentration. As we do not have information on the CO_2 from the weather data or air volume inside the farm it is fixed to 417 ppm – a recent value from 2022 according to https://doi.org/10.56028/aetr.4.1.470.2023. The *Output* of the model are the two state variables describing the dry weight. Since they do not need to be differentiated in the further investigation, they are added together to obtain the total dry weight $\mathrm{dw} = (x_{\mathrm{nsdw}} + x_{\mathrm{sdw}})/1000$ in $\frac{\mathrm{kg}}{\mathrm{m}^2}$.

Evapotranspiration

An implementation of a model for lettuce evapotranspiration is available in the plant definition. It is based on the Penman–Monteith equation with crop coefficients from @lópez_mora2024. But it yielded unrealistically high results. The source of this inconsistency was not further investigated, since irrigation is no focus in this study. Instead, a pessimistic assumption on the water use was made to dimension the water pump and judge its energy consumption. It still shows inconsequential power draw in comparison to the lighting system.

4.3.2 Leaf Environment

The leaf environment simply consists of a summation to calculate the total radiation from natural and artificial sources as well as the model `Buildings.Fluid.MixingVolumes.MixingVolume`. The mixing volume requires three static inputs. A fluid definition, the volume size and the nominal mass flow. The fluid is taken to be `Buildings.Media.Air "Moist air"` – the standard air environment following the documentation of the Modelica Building library. The volume is passed along to be defined later in the north-east, north-west, south-west and south-east facing instances. Respective for the four sides of the building. The nominal mass flow depends on the rest of the implementation. Not too much thought is given here since according to the documentation, it is mostly used for numerical robustness. It is set to a small value now and later filled in with the average of the maximum air flow for the four farms of around $90\,\frac{\mathrm{kg}}{\mathrm{s}}$. The 'radiation_total' block takes the shaded plus artificial radiation $R_\mathrm{S} + R_\mathrm{A}$ as *Dynamic Inputs* and *outputs* the total irradiance R_T. For the mass and heat flows there can be no definition of input and output since the flow direction is dynamically calculated by the simulation.

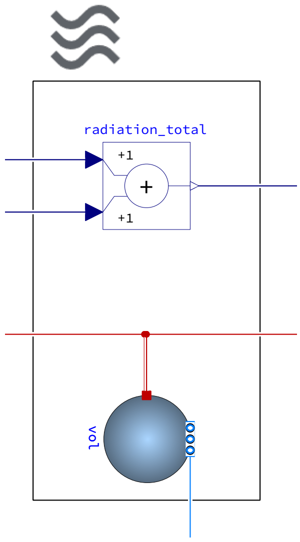


Figure 4.2: The leaf environment in the simulation.

The mixing volume model is also able to handle trace substances like water and CO_2. This is not used in our implementation but offers possibilities to simulate humidity and elevated carbon dioxide levels in the future.

4.3.3 Illumination

Now that the relevant parts of the controlled system are implemented, we can look at the engineered system. First the illumination control is modeled. For this the natural radiation is needed as a control signal. Conveniently there are already models implemented, computing the components for direct and diffuse radiance from the weather data. The ground reflected radiation is part of the diffuse irradiance in this context. These models as well as the 'weaBus' carrying the weather data can be seen on the left of the shading model in Figure 4.3. The surface tilt and azimuth are taken as static parameters by these blocks. Tilt is set to 90° as the farm is placed on the side of a building. The azimuth is passed along to the instance definition respective the orientation of the building face the farm is mounted to. Additionally, the 'HDifTilIso' model can define the ground reflectance. This is left at the standard value of the model definition which is 0.2.

Shading

With the natural radiation taken care of, the awning is examined more closely. Shading cloths for greenhouses are usually chosen by their diffusion percentage. That is the proportion of light which will not pass through. They are available in a range from 20 up to 80 % diffusion. An industry standard shading cloth with 40 % is chosen as Germany does not experience extreme levels of irradiance. As such the awning extending the fabric is simply modeled as a multiplication block governed by a P controller. The controller is limited from the values 0.6 to 1. Effectively letting 60 to 100 % of the natural radiation pass into the farm according to the incident intensity. Lettuce experiences light stress above 290 $\frac{\mu\mathrm{mol}}{\mathrm{m}^2\,\mathrm{s}}$ and so the light set point is determined to be at this value @chen2022. The output of the shade block is multiplied by 2.02 $\frac{\mu\mathrm{mol}}{\mathrm{W\,s}}$ to get PAR from the suns' radiation @reis2020. This is then fed back to the P controller. Notice that the conversion factor at this point is different from the one used in the plant model. This is because here we are converting full spectrum light to the photosynthetic relevant range from 400 to 700 nm. With the plant model input, we already had this range given and just wanted to exchange the units.

Natural irradiance R_{N} contained in the weather data is the *Dynamic Input* for the block. The *Output* is the shaded radiance R_{S}.

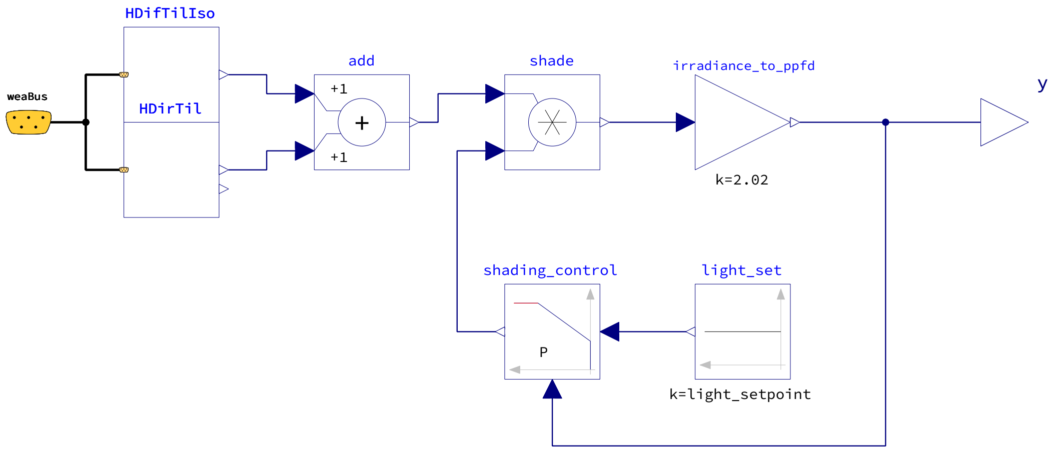


Figure 4.3: The model calculating the shaded irradiance.

LED

The LED model now takes the shaded radiation and calculates the DLI for it. This is done by an integration block with a daily reset. Then the signal is sampled at the end of each day and subtracted from the optimal DLI. Which is 14.4 $\frac{\text{mol}}{\text{m}^2\,\text{d}}$ for lettuce according to @pennisi2020. As sometimes the actual irradiance will be above the optimal value, a limiter rectifies the signal. This is to remove nonsensical negative values. As we can not take light away with the LEDs. Then the time to achieve optimal DLI is calculated with the actual PPFD output of the lighting system. The chosen LEDs were already introduced in Section 3.2.3. Their light flux is 218.28 $\frac{\mu\text{mol}}{\text{m}^2\,\text{s}}$. Time to achieve optimal DLI is calculated and compared to a timer. It is started every day if supplemental lighting is needed. A simple on/off controller then switches on for the requested time interval.

This enables the *Outputs* 'ppfd_out' and generated waste heat at the red heat port. R_A and $\dot{Q}_\text{R}$ respectively in the system definition (3.5). Waste heat is calculated from the efficiency of 62.2 % for the chosen light fixture. Also, the total power output is given. For this the power draw per square meter of 77.76 W is multiplied by the growing area. This area is defined later in the relevant instances. The *Dynamic Input* as discussed before is the shaded radiation R_S.

Note that this control waits until the end of the day to calculate the missing DLI. As such it turns on at 00:00 the next day and illuminates during nighttime. This might be good behavior considering electricity prices, but is not applicable everywhere. For instance if the system is installed at residential buildings, inhabitants would not want to be illuminated during sleeping hours. In this work no time optimal control for the lighting system is considered. Only optimality regarding the total irradiance is aimed for.

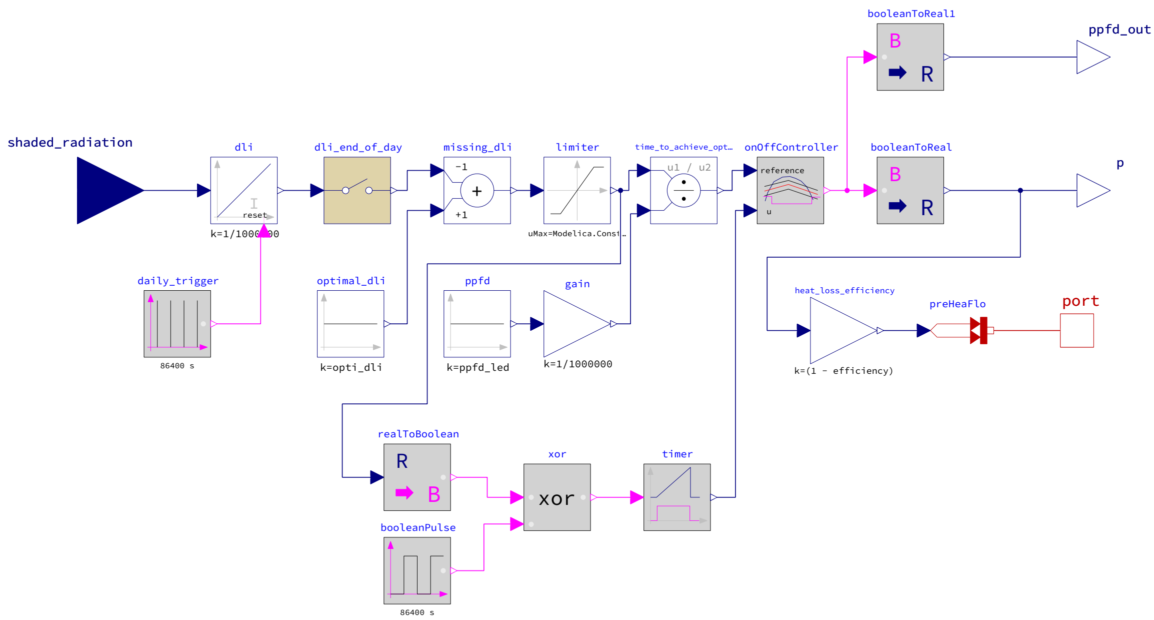


Figure 4.4: The LED model and control circuitry.

The model was verified by visually inspecting the output as can be seen exemplary in Figure 4.5. On the first day (4.85 Ms - 4.92 Ms) the incident radiation (red) is high with a resulting DLI of 17.48 $\frac{\mathrm{mol}}{\mathrm{m^2\,d}}$. Consequently, the supplemental lighting (blue) is not turned on. The second day shows less natural light (13.21 $\frac{\mathrm{mol}}{\mathrm{m^2\,d}}$) and therefore the LEDs are turned on at 00:00 (5.01 Ms) the next day. The third day (5.01 Ms - 5.1 Ms) is quite cloudy, hence the artificial light is turned on for longer. This also highlights the non-optimality of the timing as it illuminates into the sunrise of the next day. A smarter lighting system can be the grounds for further research.

4.3.4 Atmosphere

Envelope

For the simulation of the atmosphere control, we also consider the envelope. The model for its heat transfer is introduced in Figure 4.6. Weather information is again carried by the weather bus. It is used in 'pre_tem' to prescribe the outside temperature onto the heat port of the convection component. Wind direction and speed is also taken from the weather data and fed to 'conv_out'. The component takes the area over which

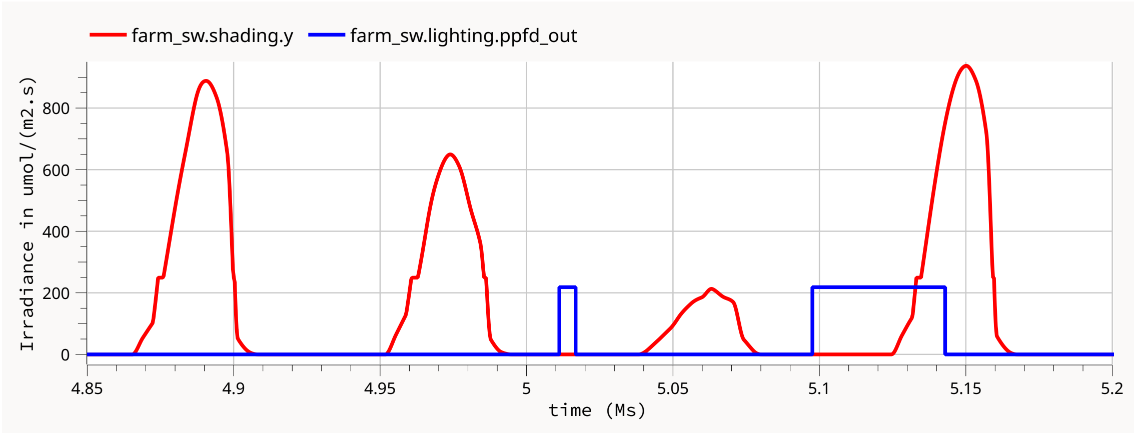


Figure 4.5: LED model validation.

the convection is happening, the roughness of the solid material, the azimuth and the tilt as input. The area and azimuth are again passed to the later instances. Since the envelope is made of glass, the roughness is set to `SurfaceRoughness.VerySmooth`, following the documentation. Tilt is fixed at 90°. Next the data record 'glass' can be seen in the bottom of the model. It was taken from the Buildings library with the thickness parameter adjusted to 5 mm. This material definition as well as the envelope area are passed to the 'conduction' component. Then the convection facing the farms' interior is connected to the aptly named heat port. When specifying the air direction for forced convection, we have to be thorough. Usually for weather data it is given as a cardinal direction. However, air flow in our farm will be mostly upwards. Checking in the model the forced convection coefficient h_{f} is calculated with $W = 1$ for windward surfaces and $W = 0.5$ for leeward surfaces. There is no further distinction made. A 90° flow along the surface is considered windward in the documentation and as such the value $W = 1$ is applicable for upwards air movement. So the constant $\pi - \text{azimuth}$ is fed to the component as the air direction, insuring it is normal on the surface. The air speed is calculated from the fluid flow in the farm and input here. Heat gain from solar radiation is considered as well. For this the shaded radiation is multiplied by the solar heat gain coefficient. Its value for windows is typically in the range of 0.2 to 0.7 according to the British Fenestration Rating Council. A value of 0.5 is used in our simulation.

With this we have defined the *Inputs* as the shaded radiation R_{S}, air speed inside the farm and weather information. The *Output* is heat flow information.

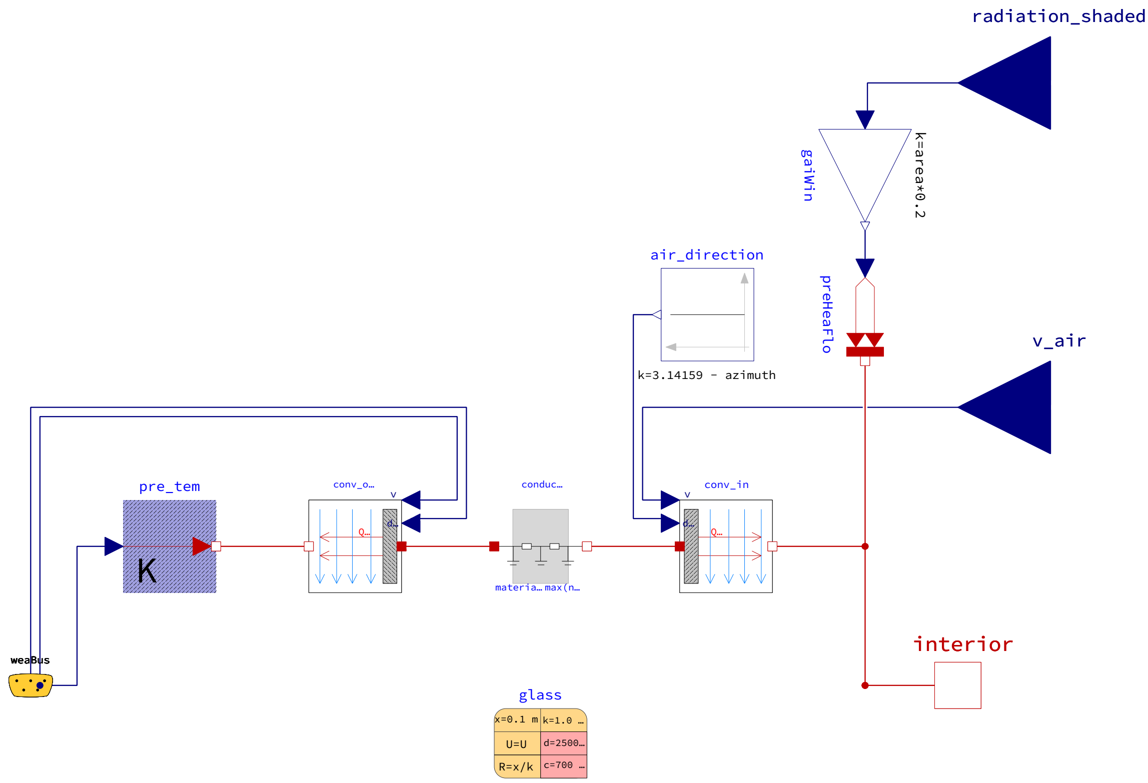


Figure 4.6: The heat transfer model of the envelope surrounding the farm.

Air Control

As elaborated previously the atmosphere control in our concept consists of simple controlled windows. The windows are modeled with `Buildings.Airflow.Multizone.DoorOperable` . At first glance it seems odd to take a door model for the implementation of windows. However, it is a "Model for bi-directional air flow through a large opening such as a door which can be opened or closed based on the control input signal y", according to the documentation needs ref. Which tells us it can also be used to model a window like opening. No more appropriate model was found by the author in the library. The equation governing the volume flow rate of air for the closed opening is given by

$$\dot{V}_{\text{closed}} = c_{\text{closed}} \Delta p^{m_{\text{closed}}}$$

with c_{closed} being the flow coefficient and $m_textclosed$ the flow exponent needs ref. This computes air flow through inevitable small gaps. The values for these coefficients were left at the default for the model. The volume flow rate for the open window $\dot{V}_{\text{open}}$ is given by the equation introduced in the fundamentals (2.1.3). The total air flow resulting from the operation of the opening is calculated with

$$\dot{V}_{\text{total}} = (y-1)\dot{V}_{\text{closed}} + y\dot{V}_{\text{open}}$$

according to the documentation of the model, where y is the control signal. These models need geometric information to go off of. The height of the window was fixed to 0.4 m. The widths of the single windows is added together and assumed to be equal to the breadth of the farm. These dimensions ensured sufficient air flow in summer temperatures. The area of the gaps specifying the closed window was set to $0.001\,\text{m}^2$. A small value, since we would want to have small gaps for the windows, to not allow unwanted airflow.

The actual pressure difference Δp needed to calculate the air flow is given by the components 'air_column_top' and 'air_column_bot'. Its calculation was already introduced in Section 2.1.3. With 11.25 m being the height of the two air columns respectively. That is half the height of the building. The geometric calculations are introduced later in the instance definitions.

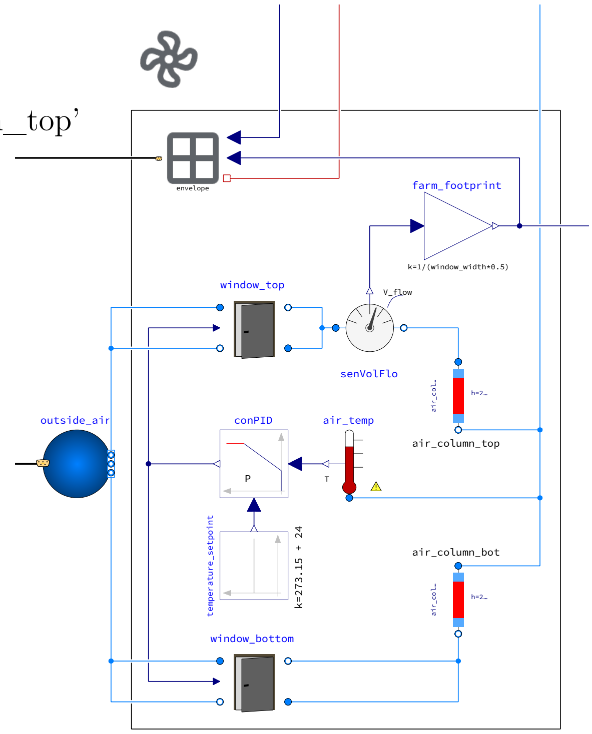


Figure 4.7: The atmosphere control.

From this volume flow through the farm, also the air speed is calculated with $v_{\text{air}} = \dot{V}_{\text{total}} / A_{\text{footprint}}$. The footprint area takes the window width and depth of the farm of 0.5 m into account $A_{\text{footprint}} = w_{\text{window}} * d_{\text{farm}}$.

Control of the windows is taken over by a simple P controller. Its set point is fixed to 24 °C, the optimal temperature for lettuce growth following needs ref.

Next the power consumption is evaluated in Figure 4.8. But how do we model this? The motors actuating the windows are active when there is a change of the control signal. So to get this information, the derivative is taken. This makes sense as it is higher when there is more change. Then the absolute value is computed and compared to a threshold value. This is needed since we do not have to actuate the motors for any miniscule change. An on / off controller then turns the motors on when the threshold is passed. The value for this boundary is taken from the simulation data. No extensive analysis is taken here, since the resulting power consumption is mostly negligible. The chosen motors introduced in 3.2.3 have a wattage of 26 W. As argued before, two of them are deployed. So the output of the controller is multiplied with 52 W in the 'booleanToReal' block.

Inputs and Outputs.

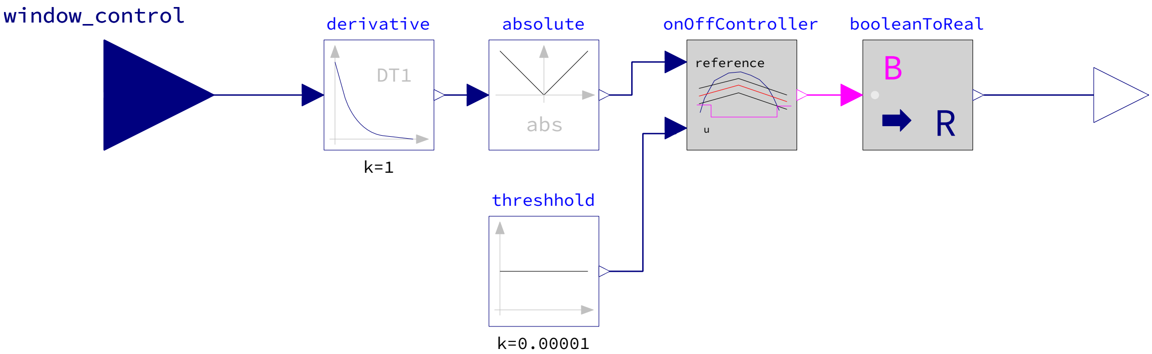


Figure 4.8: The blocks modelling the energy consumption of the window control.

4.3.5 Water System

As elaborated before in 3.2.3, the chosen pump has a power draw of 4 kW. We want to ideally run it during the day to make use of the solar array. So for the model it is assumed to be active at full power anytime the sun shines, to fill up the water tanks on the roof. These then supply the irrigation system during nighttime. When `weaBus.HGloHor` – the global horizontal radiation – is greater zero, the pump is switched on. It is argued that this is a sufficient pessimistic assumption to not underestimate the systems' power usage.

Listing 4.2: Model implementing the power requirements of the pump.

```
model pump
  Buildings.BoundaryConditions.WeatherData.Bus weaBus;
  Modelica.Blocks.Interfaces.RealOutput p;

equation
  if (weaBus.HGloHor > 0) then
    p = 4000;
  else
```

```
    p = 0;
  end if;

end pump;
```

So with this the *Input* to this block is the weather data and the *Output* is the power requirements for the water system. Now that we have examined all the models part of the engineered system we have defined before, other implemented systems are discussed. Starting with energy generation through a solar array.

4.3.6 Photovoltaics

For solar installations, there exists the 'pvSimple' model within the Buildings library. This is implemented according to its documentation. The systems' voltage is fixed at 48 V. Azimuth and Tilt are set to 'south' and 30° respectively. There might be more optimal values, this was however not further investigated. The area of the solar array is set to be equal to the roof area of the building, which is 1212 m^2. This value is calculated from the 3d-model needs ref. Still two more parameters need to be defined. First the fraction of the area which is covered by active panels is set to 0.8. And the efficiency of the panels is assumed to be 20 %.

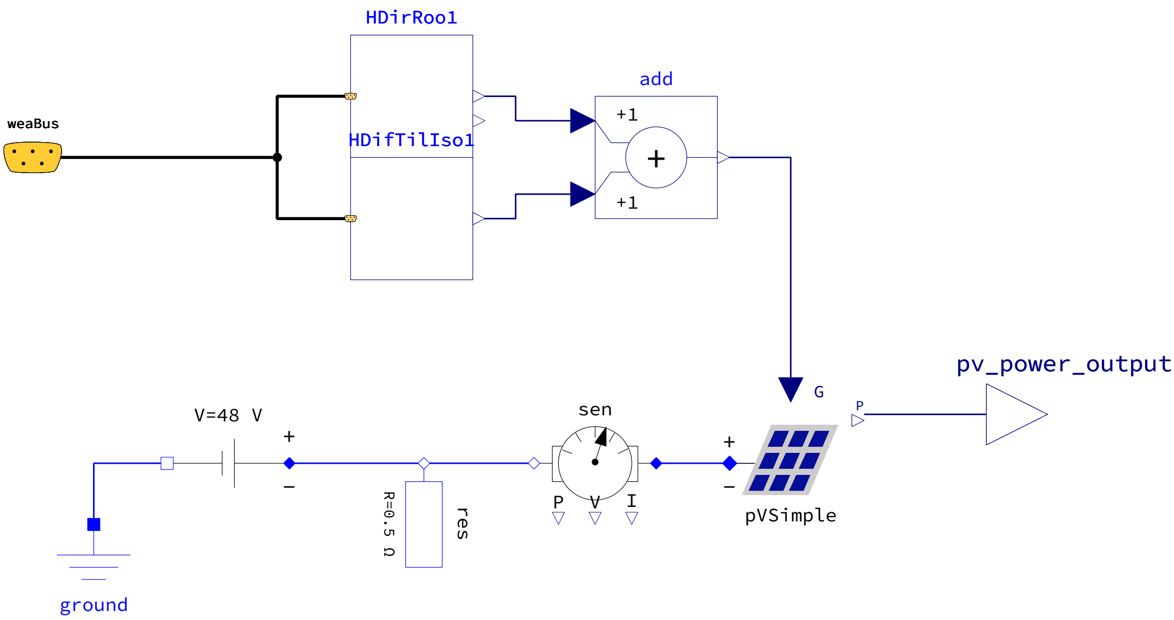


Figure 4.9: The model for the solar array.

4.3.7 Physical Environment Model

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

4.3.8 Instance Definition

depth of the farm window width height of the building Geometric calculations! Do a table with these.

4.3.9 Building

4.3.10 City Environment

The .eps file containing the needed information is taken from needs ref.

4.3.11 Full system simulation

With all the necessary building blocks introduced now, we can take a look at the final implementation. The four farms are connected up to the building, the city environment and some analysis blocks. This is shown in Figure 4.10.

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.

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.

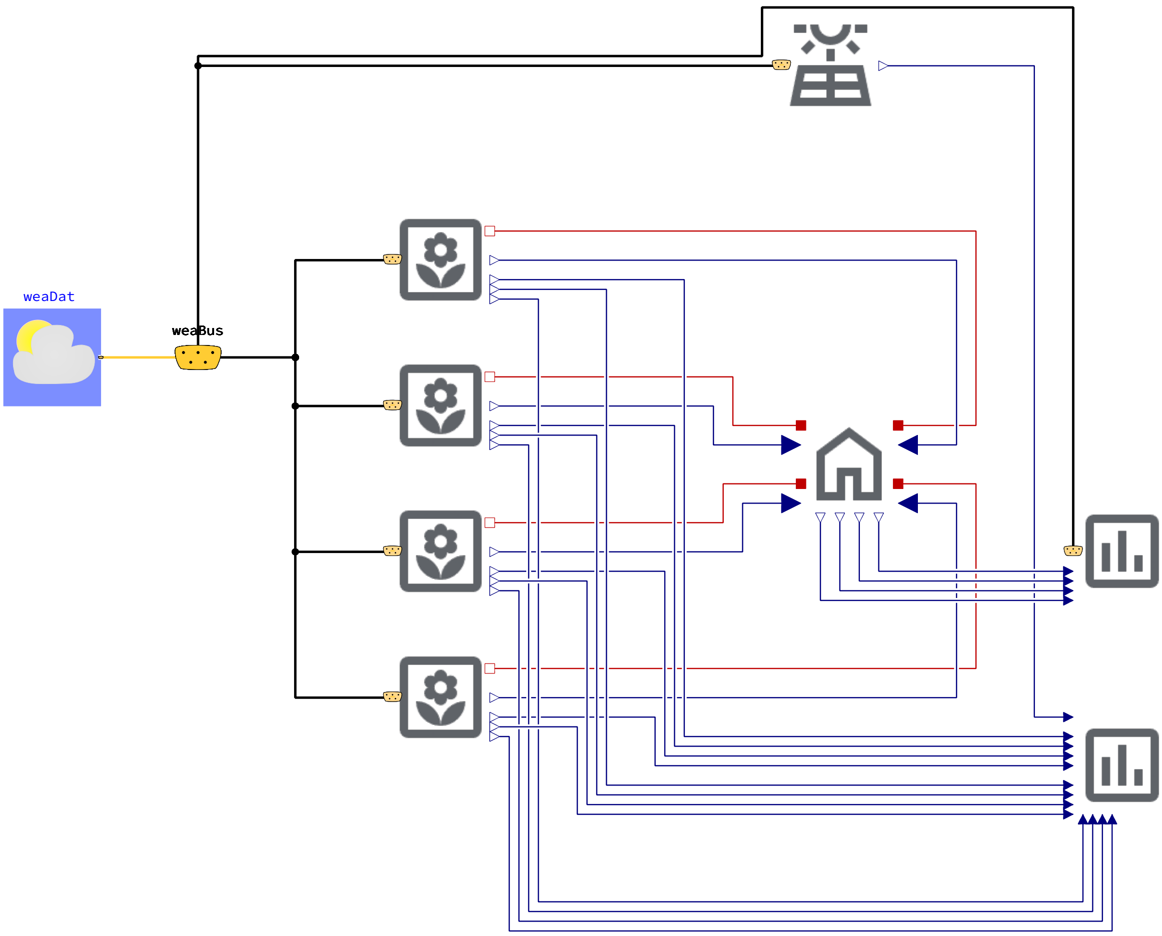


Figure 4.10: The full simulation.

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. Smarter lighting system.

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.

Sort acronyms alphabetically in the end.

List of Figures

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