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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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Danksagung

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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

SVP Saturated Vapor Pressure

RH Relative Humidity

HVAC Heating, Ventilation and Air Conditioning

Contents

Chapter 1

Introduction

1.1 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, the 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 allocation 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.

1.2 Procedure

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

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

Ok to separate into two sections or better alles aus einem Guss?

Chapter 2

Fundamentals

To , we need to illuminate a few different systems. $\dot{m}$

2.1 Thermodynamics

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

2.1.1 Types of Heat

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

2.1.2 Heat Transfer

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

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

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

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

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

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

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

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. Looking at incoming radiation, we have the characteristic value of absorptivity α (-). This is combined with the incident radiation $\dot{Q}_{inci}$ (W) to obtain

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

for captured heat flux by a material.

Conveniently these physical relations are already modeled in the Modelica Standard Library and further built upon with the Buildings Library. Should I introduce here already the modelica models which implement this?

2.1.3 Other relevant thermodynamic properties

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

2.2 Agricultural and CEA Basics

To understand CEA, we need to understand photosynthesis.

This will help us to understand what technology is needed in a modern agricultural system. And how this influences the biological system we are trying to take care of. This is important as we are trying to gauge the yield output of the crop later.

In the center of CEA stands the plant. The environment is crafted to provide optimal conditions.

2.2.1 Illumination

For illumination a few factors are of importance. Instant irradiance and time dependent factors like dli and dark period.

For irradiance there are two important factors which define instant irradiance. Spectrum and irradiance power.

Irradiance on a tilted surface

Solar spectrum and photosynthesis

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

For quantifying *spectrum* and *instantenous intensity* we will introduce Photosynthetically Active Radiation (PAR) and Photosynthetic Photon Flux Density (PPFD). As discussed before we want to How do we quantify the solar irradiance Plants use solar radiation in the spectrum from 400 nm to 700 nm needs ref for photosynthesis. This is only a portion of the actual solar radiation which is hitting earth. For the *natural* solar radiation in the context of plant growth, the concept of PAR is most often used. This describes the solar radiation which lies inside the aforementioned range for photosynthesis and can be calculated with a simple conversion factor @reis2020. Meanwhile when using *artificial* lighting, PPFD is used to describe the relevant radiation. PAR and PPFD quantify *light spectrum* and *instantenous intensity*. They both carry the same unit and except for their natural or artificial origin, can be treated the same.

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

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

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

Typical values for solar radiation and artificial illumination.

2.2.2 Irrigation

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

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

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

2.2.3 Atmosphere

As elaborated before, optimizing photosynthesis -> chemical components.

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

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

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

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

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

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

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

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

Chapter 3

Theoretical Analysis and Approach

This chapter presents an analysis of the system and literature regarding previous work. 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. From which the main goals of this work are extracted. This enables us to map out a solution proposal. 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 our green companions. 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* and therefore outside world 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 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 reveal the properties of interest which are still missing for our system definition (3.1).

3.1.2 Properties of Interest

Controlled System

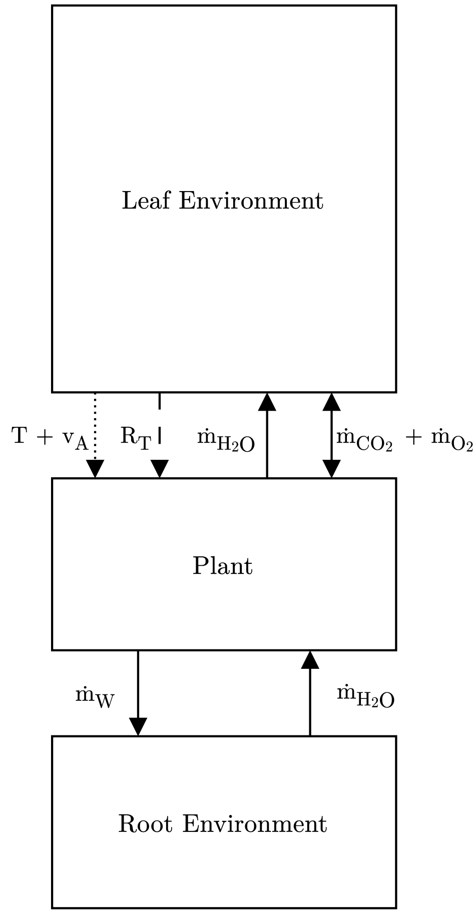
Beginning with the controlled system again, we illuminate the interactions between the plant and its environment. The root system is relatively straight forward to manage. We need to supply water and nutrients while cleaning out waste products. These are modeled as mass flows. Water and substances dissolved 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 transport the nutrients up into its body. This movement is fueled by transpiration. About 99 % of the $\mathrm{H_2O}$ 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 controlled system. These are however not the only attributes of interest.

As shown later in the Yield Analysis there are two other features of the atmosphere we need to take a closer look at. These are inputs to the yield model and are not consumed in contrast to the other characteristics. These properties are informational in nature. They are air temperature T and air speed v_{A}. 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 as dashed and data flow dotted. Now that we looked at the target system, the next section will talk about its supervision.

Figure 3.1: The plant and its immediate environment



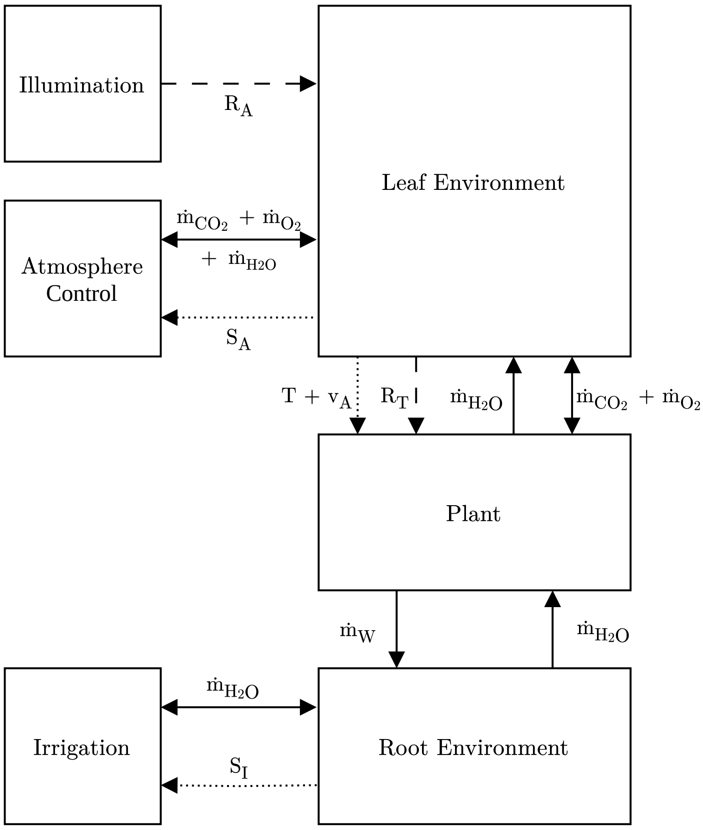
Engineered System

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 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.

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. For the control to function there needs to be some form of feedback. Sensors to capture the relevant properties temperature, air speed and the mass concentrations are placed in the air volume. They are aggregated with the atmosphere control signal S_{A}.

For irrigation, we again describe the water flow with any dissolved materials as $\dot{m}_{\mathrm{H_2O}}$. 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. Subsequently, we will highlight the context of our system.

Figure 3.2: A wrapped figure going nicely inside the text.



Context

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

The weight of the different properties are discussed in the next chapter.

Trace substance.

Analyzing the important attributes will give us a clear view which parameters are free design variables. And which are constraint by other properties.

This information is extracted from the objectives this work tries to optimize. Minimizing energy consumption and maximizing yield. These two goals are subjected to a sensitivity analysis in the following sections. This helps us to identify the most relevant parameters.

In this application, we can differentiate between different types of flow.

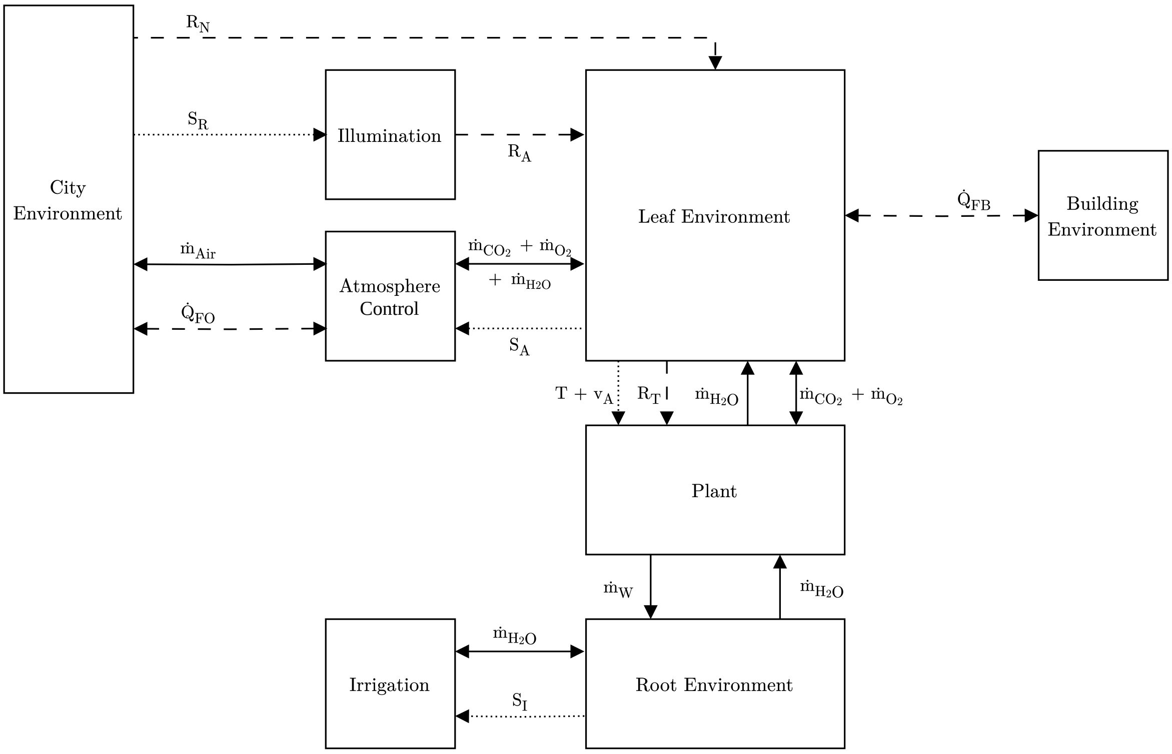


Figure 3.3: System partitioning and important flows

1. Mass flows $\dot{m}$ – continuous lines
2. Energy fluxes – dashed lines
   a) Pure heat flows $\dot{Q}$
   b) Radiation R
3. Informational flows – dotted lines
   a) Temperature T and air speed v_A
   b) Control signals S

These informational factors are not considered in the block diagram, s

Behind these lie the technical systems we are trying to

Illumination will be separated into two parts for our inquiry. The radiation provided by the

3.1.3 Energy Analysis

To be able to evaluate the energy impact of the different technical subsystems, we will look at current vertical farming system.

Let us first examine current CEA and vertical farming approaches to get a better understanding of the solution methods and shortcomings. Current solutions try to achieve high degree of automation and full control over the environment. This results in high energy

Companies such as ... and ... try to seperate the plants completely from the elements and control the environment they are in fully. This of course is great for reproducibility and quality. However as we will show later in chapter 3 current commercially operating farms with this approch have one main problem. Energy consumption. This makes them economically less competitive to traditional agriculture and shifts the resource usage from water and land area to energy. Not ideal for Germany, a country which still relies to ... % on fossil fuels for its energy production needs ref.

Commercial Farms

In recent years, hype surrounding vertical farming has slowed significantly. Multiple commercial endeavors declared bankruptcy needs ref. 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. This does not provide deep insight into the problematic subsystems. However, it validates the foundational assumption to minimize energy need.

Aerofarms – https://en.wikipedia.org/wiki/Controlled-environment_agriculture

Research Farms

As introduced in the fundamentals 2.2, there are three technical systems to take care of plant growth. Irrigation, illumination and the atmosphere surrounding the plant. Multiple studies have analyzed the different technical subsystems and their influence on energy need. A meta study revealed that ... % of energy is consumed by lighting systems needs ref. This already supposes energy efficient LEDs. On second place HVAC systems consume about ... %. Irrigation is mostly negligible.

A Life Cycle Assessment study comes to the conclusion that tighter integration with city infrastructure is indeed needed. We will present such a system in 3.2.

3.1.4 Yield Analysis

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

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

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

Experiments

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

Simulations

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

Instert picture of plant model.

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

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

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

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

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

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

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

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

From the first point we can deduct t

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

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

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

Define plant system.

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

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

3.1.5 Conclusions from the analysis

3.2 General Concept

3.3 Feasibility

Metrics to evalute feasibility of the concept:

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

3.4 Energy System Architecture

3.4.1 Choice of Components

Chapter 4

Showcase of Example Unit and Simulation

4.1 Introduction to the Simulation Environment

4.2 Introduction to the developed models

4.2.1 Plant Model

Evapotranspiration

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

Yield

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

4.2.2 Physical Environment Model

4.2.3 LED Model

4.2.4 Pump Model

4.2.5 Air Conditioning Model

Note that CO_2 concentrations are not dynamically calculated in the simulation and the humidity contribution from the plants is not considered. The reason for this, is that the air volume component allowing for dynamic calculation led to frequent convergence errors not further investigated in this work. The chosen value for CO_2 is 365 ppm, which is an average value for the atmosphere https://doi.org/10.1111/j.1365-

3040.2007.01641.x. For the VPD calculation, humidity levels are taken from weather data and temperature from the farm air volume.

4.3 Simulation Architecture

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

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

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.

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