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

Bachelor's (oder Master's) Thesis
on the topic

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

by

Name Surname
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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 more 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 hard to control, 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 profitably grown is limited. 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, as 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

2.1 Thermodynamics

How do I cite best here? Whole section is based on @cengel2003.

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 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 is the area through which the conduction takes place, L is the distance and ΔT 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 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

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

where T is the material temperature, σ is the Stefan-Boltzmann constant and T_{surr} 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 $\dot{Q}_{inci}$ 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.

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 granuarly.

Typical values for solar radiation and artificial illumination.

2.2.2 Irrigation

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

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

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

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 Architectural Approach

3.1 Energy Analysis

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.

3.2 Presentation of the 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

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