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

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Abstract

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

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 cause shifts in climate which can not be predicted fully. What is certain however, is that current climate and weather patterns will drastically 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 reliability might not be given 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, depending on the irrigation technology utilized. 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.

For Vertical Farming, there are two main obstacles which hold back adoption as identified by the author. One, only a small range of plants, mostly confined to leafy greens and microgreens can be cultivated for profit in this artificial environment. Two, the energy use is orders of magnitudes higher than traditional agriculture @barbosa2015. This makes these farms economically less competitive and shifts the resource usage from water and land area to energy. Not ideal for example in Germany, a country which still relies to ... % on fossil fuels for its energy production needs ref.

Nochmal in Obsidian checken für Notizen zu optimaler Introduction Unterteilen in einzelne Sections oder monolithisch?

1.2 Research Question and Structure

The main 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 plant 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 used in this work. We will then look at existing commercial and academic vertical farming systems and analyze strengths and shortcomings. As reasoned later in chapter 3, the main issue holding back adoption are high energy usage requirements. The conclusions of this inquiry are the basis of the novel concept presented. To minimize energy consumption, natural light shall be used. This is accomplished by retrofitting existing building facades with the proposed system. This choice directly results in an obvious synergy. Creating an outer shell around the building envelope, to insulate it. 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. Section 3.3 stipulates requirements to judge feasibility of this study. Also, metrics to evaluate these requirements are discussed. In section 3.4 the general architecture of the novel 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 concluded. Lettuce is chosen as the crop plant and separate 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, existing models are used to set up an investigation into the thermal and energy balances for the example unit. The results are presented in section 5. Further evaluation and resulting conclusions are discussed in chapter 6. In chapter 7 the findings are summarized and areas of further interest laid out.

Chapter 2

Fundamentals

2.1 Heat Transfer

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 substracted from the system. Total heat transfered 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 Types of Heat Transfer

@cengel2003 Heat transfer can fundamentally occur in three different forms. Conduction, Convection and Radiation.

Conduction refers to heat moving through a material. It is characterised 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 transfered 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*

To be able to understand the implementation of the simulation discussed later in needs ref, we first need to introduce the basics of heat transfer. There are three different forms in which heat transfer can occur. First Conduction, which describes heat moving through a solid material. This property can be characterised by the heat conductivity k for the specific material. The mathematical model equation will be introduced later with the heat capacity in 2.1.3. Second we have Convection. This is heat transfer which happens between the surface of a solid material and a fluid. Last the transfer can occur via radiation. As the name implies this is basically heat energy transmitted with electromagnetic rediation. These will all be modeled seperately later. How about heat transfer via mass transfer? some sources also have advection - what's that? Difference between sensible and latent heat flow.

2.1.3 Other important thermodynamic properties

Explain Heat Capacity.

2.2 Systems Modelling Approach

2.3 Agricultural and CEA Basics

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

2.3.1 Irradiance

Irradiance on a tilted surface

Solar spectrum and photosynthesis

When assessing the optimal lighting conditions for plant growth, several factors need to be illuminated. Pun intended. 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).

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

2.3.2 Irrigation

Soilless Agriculture - Hydroponics - Aeroponics

Aeroponics and specially fogponic system is chosen because of the lightweight nature and ease of deployment.

2.3.3 Atmosphere

Vapor pressure - VPD CO2 concentrations

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

Chapter 4

Showcase of Example Unit and Simulation

4.1 Introduction to the Simulation Environment

4.1.1 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

4.2 Simulation Architecture

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

4.2.1 Yield Model

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

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

4.4 Results

Chapter 5

Results

Chapter 6

Discussion

Chapter 7

Conclusion and Outlook

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