V-KEMS Study Group Report

Food Security

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1 Executive Summary

This three-day virtual study group explored the challenges related to Food security. Food security presents the challenge of ensuring that everyone in the world has, at all times, physical and economic access to sufficient safe and nutritious food. This virtual study group focused on investigating causes of food insecurity, a global issue in which agriculture, supply chains and climate change play a key role. It aimed to bring mathematical scientists and other disciplines together to solve challenges of food insecurity and to promote sustainable practices. It featured talks and insights from Francesca Re Manning (University of Cambridge, Cambridge Global Food Security). In addition, the following challenges were presented to the study group:

- **Challenge 1 – Food Waste**

  The challenge focused on estimating food waste produced by the public sector. Before we can tackle food waste, we need to understand how much is being generated and by who. Our understanding of food waste from the public sector and hospitality is based on outdated and unrepresentative data. Can we use publicly available data sets about the size and composition of the public and hospitality sectors to build bottom-up estimates of food waste to inform where to focus our efforts to reduce food waste?

- **Challenge 2 – Foliar Plant Spray**

  This challenge looked into Foliar plant spray, which involves applying crop protection products (CPPs) directly to a plant's leaves as opposed to putting it in the soil. Foliar spray quality (droplet size distribution, spray volume, spatial distance and number of droplets and concentration of the CPP) can have a huge impact on the performance of the CPP and subsequently the growth, yield and quality of the crop. The question "which spray quality leads to the most efficient CPP performance" is yet to be addressed.

- **Challenge 3 – CEA Hvac System**

  This challenge looked at a vertical farm or CEA HVAC system. The aim is to maintain target temperature, relative humidity and vapor pressure deficit within the chamber while using the minimum amount of energy. All of the target factors affect each other so changing one changes the others. Also, methods of control affect multiple target factors in different ways. This leads to a complex multivariate system with multiple target parameters and multiple interlinked control methods.

Over the course of the study group, potential solutions were developed and these were presented on the final day.

2 Food Waste

2.1 Introduction

Food waste represents a global challenge which has significant economic, environmental, and societal impacts. Tackling food waste is one of the most effective ways for reducing the carbon footprint of Scotland's waste. When food waste is sent to landfills, it releases methane, a greenhouse gas many times more potent than carbon dioxide. Some of these emissions can be avoided by recycling food waste through processes like composting or anaerobic digestion. However, preventing food waste in the first place is far more beneficial as it also reduces the 'upstream' emissions, and costs, associated with growing, harvesting, processing, transporting and buying food to begin with.

2.2 Problem Statement

The challenge focused on estimating food waste produced by the public sector. Before we can tackle food waste, we need to understand how much is being generated and by who. Our understanding of food waste from the public sector and hospitality is based on outdated and unrepresentative data. Can we use publicly available data sets about the size and composition of the public and hospitality sectors to build bottom-up estimates of food waste to inform where to focus our efforts to reduce food waste?

2.3 Existing Knowledge and Definitions

Concerns regarding food waste have garnered substantial attention in recent years, with no apparent comprehensive solution emerging. In the context of Scotland, addressing these issues becomes crucial. Globally, an estimated one-third of food produced for human consumption, roughly equating to 1.3 billion tons annually, is discarded at various stages. This substantial volume not only poses economic challenges but also exerts a significant environmental toll. Resources like land, water, and energy, invested throughout diverse stages of food production and the supply chain, are utilized in a wasteful manner, intensifying the ecological impact. The magnitude of this problem necessitates tailored strategies for Scotland to mitigate its unique challenges and contribute to the broader global effort in combating food waste.

In order to attain a transparent quantification of food waste, it is crucial to distinctly outline the waste generated from every kitchen process. This research utilizes the definitions for various waste processes outlined by both the Swedish National Food Agency and those identified by Eriksson et al. [2018]. Nevertheless, relying solely on waste processes as indicators is insufficient, and additional metrics, including the quantity of food served, must be identified and precisely defined. Below we present a system model for different waste-generating processes within a kitchen.

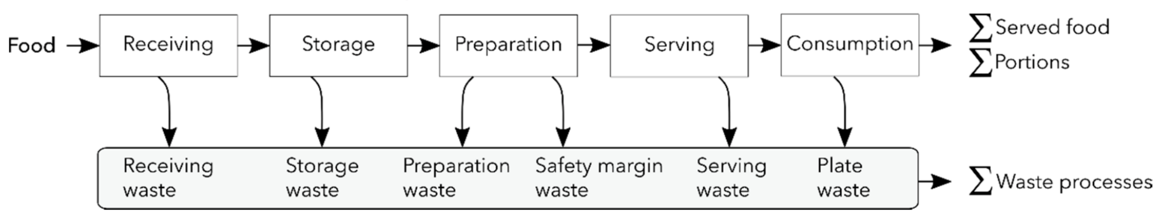

Figure 1: Different waste-generating processes within a kitchen. Food is prepared and wasted during the different steps of work in the kitchen (reproduced from Malefors et al. [2019a]).

In 2020, during the initial year of the COVID-19 pandemic, the European Union (EU) witnessed an average of approximately 127 kilograms of wasted food per inhabitant. Notably, households contributed to 55% of this food waste, amounting to 70 kilograms per person, while the remaining 45% originated from the upper tiers of the food supply chain. This data stems from the inaugural EU-wide monitoring of food waste, recently published by Eurostat. The report underscores the persisting challenge of addressing consumer food waste, a concern shared both within the EU and globally. Particularly striking is the fact that household food waste nearly doubles the combined waste from primary production and the manufacture of food products and beverages, standing at 14 kilograms and 23 kilograms per inhabitant, respectively. These sectors, which have existing strategies to reduce food waste, focus on initiatives such as utilizing discarded parts as valuable by-products. This information emphasizes the need for targeted efforts to address and mitigate consumer-driven food waste, especially in the context of the EU.

2.3.1 Definition of Different Types of Food Waste

The provided mathematical expressions detail the calculation of different types of waste in a food service context, employing a segmented approach for a more nuanced analysis. The focus revolves around waste per portion per segment and the corresponding averages, shedding light on the efficiency of waste management processes within each segment.

The first equation delineates the waste per portion per segment, signifying the ratio of the

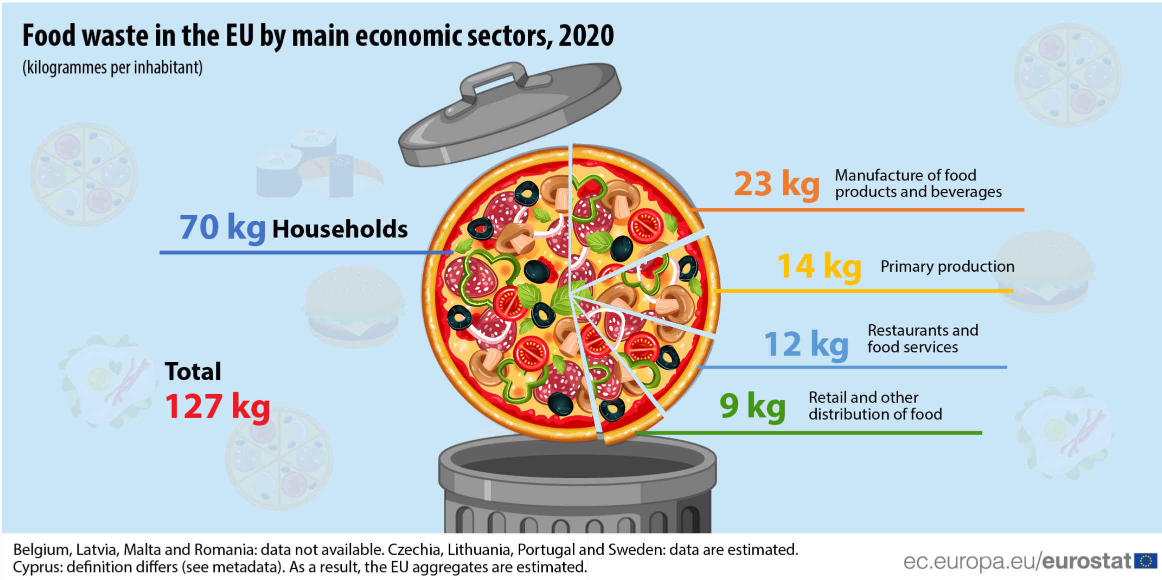

Figure 2: Different types of Waste in the EU (Source)

cumulative waste generated from distinct waste processes to the total number of portions served in a given segment. This provides a granular understanding of waste production specific to each segment, aiding in targeted interventions.

The second equation introduces the concept of average waste per portion per segment. It calculates the mean waste generated across all segments, emphasizing the need for a comprehensive overview. This metric serves as a benchmark for evaluating waste management efficiency on a broader scale.

The third equation computes the waste percentage, highlighting the proportion of waste relative to the mass of served food. This metric offers a percentage-based perspective, facilitating easy comparison and interpretation of waste levels across different segments.

Finally, the fourth equation extends the notion of average waste percentage, providing an overall average across all segments. This metric encapsulates the collective efficiency of waste management practices, aiding in the identification of trends and areas for improvement at a systemic level.

In essence, these definitions offer a robust framework for assessing and quantifying various dimensions of waste in a segmented food service context. The delineation into portions and segments allows for targeted strategies to minimize waste, fostering sustainable practices within the food industry.

$$\text{Waste per portion per segment} = \frac{\sum_{i=1}^{n} (\text{Waste from the waste processes})_i}{\sum_{i=1}^{n} (\text{Number of portions served})_i} \quad (1)$$

$$\text{Avg waste per portion per segment} = \frac{1}{n}\sum_{i=1}^{n}\left(\sum_{j=1}^{n} \frac{(\text{Waste from the waste processes})_{i,j}}{(\text{Number of portions served})_{i,j}}\right) \quad (2)$$

$$\text{Waste (\%)} = \frac{\sum_{i=1}^{n} (\text{Waste from the waste processes})_i}{\sum_{i=1}^{n} (\text{Mass of Served food}_i} \times 100 \quad (3)$$

$$\text{Avg waste (\%)} = \frac{1}{n}\sum_{i=1}^{n}\left(\sum_{j=1}^{n} \frac{(\text{Waste from the waste processes})_{i,j}}{(\text{Mass of Served food})_{i,j}}\right) \quad (4)$$

In the literature exploring food waste at the establishment level, various types have been identified, each contributing to the broader understanding of wastage in culinary settings. These include:

1. **Preparation waste:** This pertains to food discarded during the process of meal preparation, encompassing items deemed surplus or unsuitable for serving.
2. **Serving waste:** Referring to food that is served but remains unconsumed by guests, this category sheds light on factors influencing plate clearance.
3. **Plate waste:** Focused on the food picked up by guests but left unconsumed, plate waste provides insights into diners' preferences and portion sizes.
4. **Other types:** This category encompasses diverse classifications that may vary across sources, including but not limited to storage waste, safety margin waste, and other nuanced aspects associated with food disposal practices.

It is essential to note that different sources may employ distinct terminologies for these categories, contributing to the multifaceted nature of understanding and addressing food waste in culinary establishments.

Diverse entities within the hospitality sector contribute to varying quantities of food waste, exhibiting distinctive breakdowns based on the types of waste generated. The volume of food waste generated by different establishments, ranging from restaurants and hotels to catering services, is influenced by several factors such as the scale of operations, the nature of the cuisine served, and the specific practices implemented within each setting. Furthermore, the breakdown of food waste per type varies significantly, encompassing aspects like preparation waste, serving waste, plate waste, and other categories, each influenced by the operational dynamics and characteristics unique to the particular establishment. This variability underscores the need for tailored approaches to address and manage food waste within the diverse landscape of the hospitality sector. Efforts to minimize waste and enhance sustainability must consider the nuanced factors that contribute to the distinctive food waste profiles across various hospitality establishments.

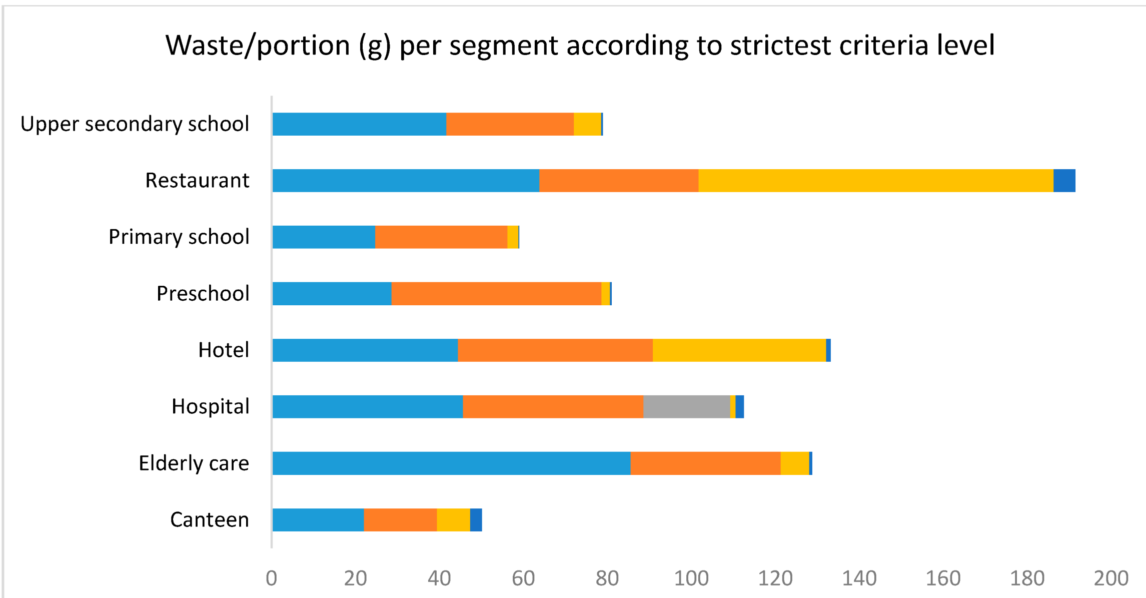

Figure 3: Contribution of different waste generation processes to total waste for the different segments: (■) "Plate waste" (■) "Serving waste" (■) "Safety margin waste" (■) "Preparation waste", and (■) "Storage waste" (reproduced from Malefors et al. [2019a]).

In the study Malefors et al. [2019b], where four interventions (awareness campaign, forecasting, tasting spoons, and plate waste tracker) in Swedish school canteens were evaluated, food waste reduction ranged from 6 to 44 grams per portion. The awareness campaign notably lowered plate waste by 13 grams per portion, surpassing the reference group's 7 grams. Forecasting and the plate waste tracker significantly reduced serving waste by 34 and 38 grams per portion, respectively, compared to the reference group's 11 grams. The plate waste tracker and forecasting were the most effective interventions, achieving greater overall reductions (44 and 34 grams per portion) than the reference group (17 grams). Tailored interventions are crucial, and organizations should develop a toolbox for sustainable food waste reduction.

In the current literature, various methods, predominantly designed for the forecasting of food waste, have been investigated, as evident in works such as those by Liu et al. [2020b,a], Tang et al. [2021]. To effectively address and minimize food waste, it is essential to gain insight into the practical realities on the ground. This involves considerations such as kitchen staff possessing a comprehensive understanding of waste, enabling the implementation of diverse mitigation measures, as emphasized by Liu et al. [2020a]. Moreover, the success of forecasting and other food waste minimization measures is significantly influenced by the practical organization of work. Factors such as complex data acquisition processes and the need for substantial backup stock in case of underestimating guest numbers play a pivotal role in determining the feasibility and effectiveness of these measures. Additionally, the practicalities of food waste reduction strategies should account for various factors, including remote work, variations due to the day of the week and holidays, seasonal fluctuations, and inherent differences between different canteens. Ensuring precision in defining terms and developing a robust mental model of on-the-ground processes is imperative for effective waste management strategies. Furthermore, it is noted that forecasting methods are likely to improve with enhancements in data quality and size, underscoring the importance of focusing on methods that enhance data quality without overly complicating the acquisition process.

2.3.2 Task List and plan of action during the study group meeting

The outlined plan involved a comprehensive approach to understanding and addressing the issue of food waste. Firstly, a thorough examination of available data provided by the proposer was essential. Subsequently, a brief literature review on system dynamics and its applications in modeling food waste was carried out. In this literature review, specific attention was given to identifying primary contributors to food waste, exploring sub-sectors with higher waste outputs. The review was initiated by Christine and Chrysoula, and the findings were documented collaboratively on HackMD. Additionally, the plan included adopting a systems perspective to address the food waste problem, potentially incorporating models identified during the literature review. Finally, the development of a decision-support tool, utilizing dynamic sliders, aimed to provide enhanced insights and facilitate more informed decision-making.

2.4 Previous Work on Food Waste

Several noteworthy papers provide valuable insights into the dynamics of food waste:

- A System Dynamics Model for Evaluating Food Waste Management in Hong Kong, China: Lee et al. [2018] models the effectiveness of food waste policies, including education and charging. It considers different sectors, such as household food waste and commercial & industrial sectors, utilizing both a quantitative System Dynamics (SD) model and a causal loop diagram.

- A System Dynamics-Based Approach to Help Understand the Role of Food and Biodegradable Waste Management in Respect of Municipal Waste Management Systems: [Malefors et al., 2019b] This paper focuses more on waste management rather than waste reduction.
- Tackling Food Waste: A System Dynamics Approach to Analyzing Food Waste in Wholesale Markets and Developing Targeted Interventions for Sustainable Operations: This paper concentrates on supply chains, making it potentially less relevant in this context.
- Food Waste Reduction and Food Poverty Alleviation: A System Dynamics Conceptual Model: [Galli et al., 2019] This paper explores the connections between food waste and food recovery, with a focus on reducing wasted food through food donation (food surplus reduction and food poverty alleviation). It includes a useful figure complementing insights from an earlier study group.
- System Dynamic Model for Restaurant's Food Waste in Surabaya: [Mahachandra, 2021] includes a useful causal loop diagram that could be relevant here. It considers the possibility of fining customers for leaving food and changing the frequency of food orders.
- Development of a System Dynamics Model to Guide Retail Food Store Policies in Baltimore City: [Zhu et al., 2021] This interesting paper explores the establishment of a "staple food ordinance" in Baltimore, USA, requiring shops to always offer certain foods, typically healthy options. The paper utilizes System Dynamics to model food waste and set the staple food ordinance appropriately.

2.4.1 Some other interesting papers

Food waste in hospitality and food services: A systematic literature review and framework development approach (2020) General overview should anyone be interested in the state-of-the-art - indeed the gaps in research are aplenty, there are problems in generalizability (research being done in silos), research missing for different geographical locales etc.

Food waste accounting along global and European food supply chains: State of the art and outlook (2018) Provides overview of several methodologies of quantifying food waste at a global/EU level, different waste streams captured etc. Interesting quote: *"Current estimations of food* *loss and waste generation range between 194–389 kg per person per year at the global scale, and between 158–298 kg per person per year at the European scale."* Quite a breadth of estimates! It could be interesting to go deeper into the studies compared and see individual methodologies for inspiration.

Quantification of food waste in EU Member States using material flow analysis (2020) in several paywalled articles I've seen mentions of Material Flow Analysis as a method for food waste modelling. This presentation has a pretty nice overview of that, including conceptual scheme of a proposed model. Perhaps this one could help with the system dynamics approach as a source of ideas for system characteristics to consider. Interesting insight - albeit from 2010, however this is likely still true - is that plant based food waste accounts for majority of food waste, with veggies and fruit leading the pack.

2.5 Waste per sector

2.5.1 Overview of our work

This report provides a comprehensive overview by conducting a detailed analysis of food waste within the cafe sector in Scotland on a per-employee basis. The aim is to establish a foundational understanding that extends beyond cafes to encompass other critical hospitality sectors like hotels and restaurants. Additionally, this analysis lays the groundwork for extending the examination to diverse sectors, including the hospital industry. By focusing on the cafe sector as a starting point, the study aims to uncover insights and patterns that can inform broader strategies for mitigating food waste across various segments of the hospitality industry, contributing to a more holistic approach to waste reduction and sustainability.

2.5.2 Analysis of Cafe data

- **Linear Regression Models:**

  First, three distinct linear regression models are employed to unravel intricate relationships within the data, scrutinizing the impact of the number of employees, daily covers, and both variables combined on daily waste.

Table 1: Regression of Waste Daily on Covers Daily

Observations	23
Dependent variable	Waste.Daily
Type	OLS linear regression

F(1,21)	33.01
R^2	0.61
Adj. R^2	0.59

	Est.	S.E.	t val.	p
(Intercept)	2.60	2.84	0.92	0.37
Employees	1.07	0.19	5.75	0.00

Standard errors: OLS

Table 2: Regression of Waste Daily on Covers Daily

Observations	16 (7 missing obs. deleted)
Dependent variable	Waste.Daily
Type	OLS linear regression

F(1,14)	11.13
R^2	0.44
Adj. R^2	0.40

	Est.	S.E.	t val.	p
(Intercept)	3.82	4.06	0.94	0.36
Covers.Daily	0.05	0.01	3.34	0.00

Standard errors: OLS

Table 3: Regression of Waste Daily on Employees and Covers Daily

Observations	16 (7 missing obs. deleted)
Dependent variable	Waste.Daily
Type	OLS linear regression

F(2,13)	8.70
R^2	0.57
Adj. R^2	0.51

	Est.	S.E.	t val.	p
(Intercept)	-0.15	4.20	-0.04	0.97
Covers.Daily	0.01	0.02	0.58	0.57
Employees	1.05	0.53	1.98	0.07

Standard errors: OLS

Conducting three distinct linear regression models has proven to be instrumental in unraveling intricate relationships within the cafe data. Specifically, our analysis scrutinizes the impact of key variables, namely the number of employees, daily covers, and their combination, on daily waste. Notably, the findings underscore a substantial dependence of daily food waste on the number of employees. This insight illuminates a critical factor influencing the generation of waste in cafes.

The linear regression models provide a quantitative lens through which we gain valuable insights into the nuanced dynamics of waste generation. The emphasis on the number of employees as a significant predictor elucidates the pivotal role played by the workforce in influencing the daily waste output. Such revelations offer actionable intelligence for cafe operators, suggesting that optimizing staffing levels may not only enhance operational efficiency but also contribute to effective waste management.

In essence, the application of robust regression analyses has unveiled key determinants of daily waste in cafes, with implications extending beyond statistical significance. This understanding positions stakeholders to make informed decisions and implement targeted strategies, fostering sustainable practices and minimizing the ecological footprint of cafe operations. The analytical journey undertaken reinforces the importance of data-driven insights in shaping responsible and efficient waste management practices within the hospitality industry.

- **Additional Regression:**

- Further examinations are conducted, focusing specifically on the daily waste per employee and daily waste per cover through dedicated linear regression models.

Table 4: Regression of Daily Waste per employee on Employees

Observations	23
Dependent variable	Daily.waste.per.employee
Type	OLS linear regression

F(1,21)	1.22
R^2	0.05
Adj. R^2	0.01

	Est.	S.E.	t val.	p
(Intercept)	1.82	0.33	5.48	0.00
Employees	-0.02	0.02	-1.10	0.28

Standard errors: OLS

This nuanced insight highlights the complexity of waste dynamics within cafes. While the overall daily waste may be influenced by the total workforce, the relationship becomes less evident when considering waste on a per-employee basis. Factors beyond staffing levels may contribute to the observed patterns, such as variations in operational practices, menu structures, or customer behaviors.

- **Visualization Techniques:**
  - A comprehensive pairs plot is generated, offering a visualisation or assessing relationships among multiple variables. Additionally, scatter plots are crafted, employing color-coded distinctions to reveal size-related patterns based on the number of employees.
- **Data Segmentation:**
  - The dataset undergoes segmentation based on cafe size, differentiating between large and small cafes. Pairs plots for the segmented data provide nuanced insights into patterns associated with varying cafe sizes.
- **Histograms:**
  - Histograms are presented to visually represent the distribution characteristics of key metrics, including daily waste per cover, daily waste per employee, and the ratio of daily waste to the combined number of employees and daily covers.

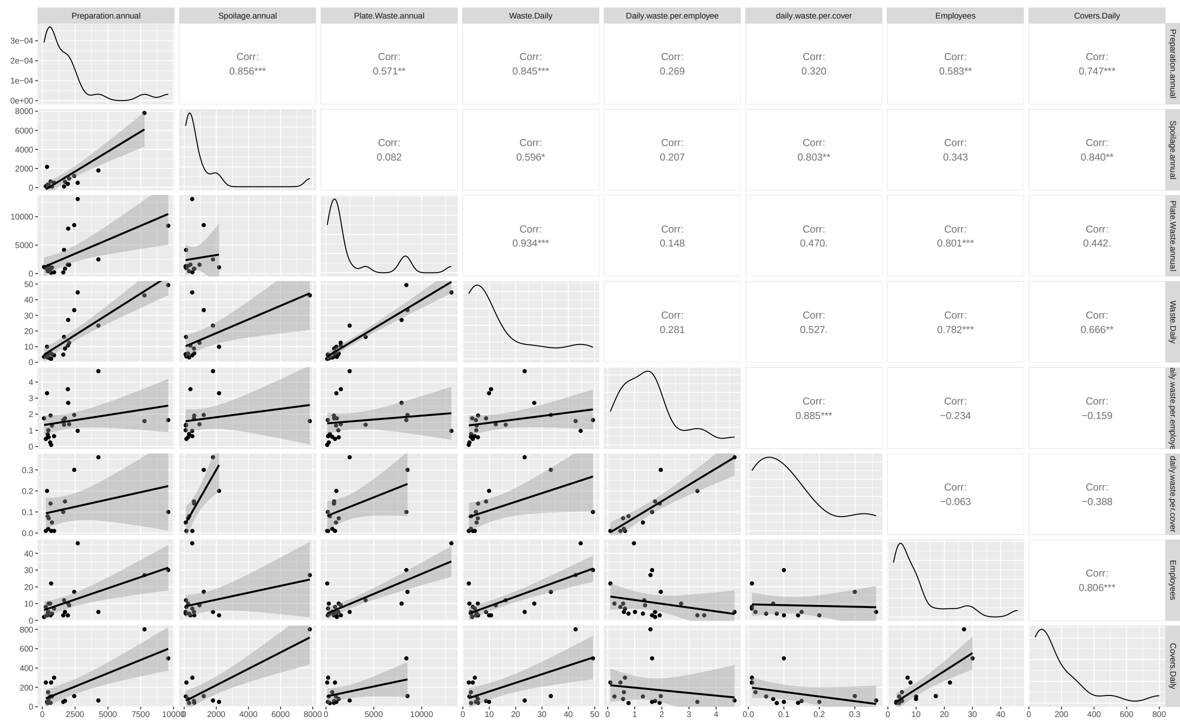

Figure 4: Pairs plot of cafe data

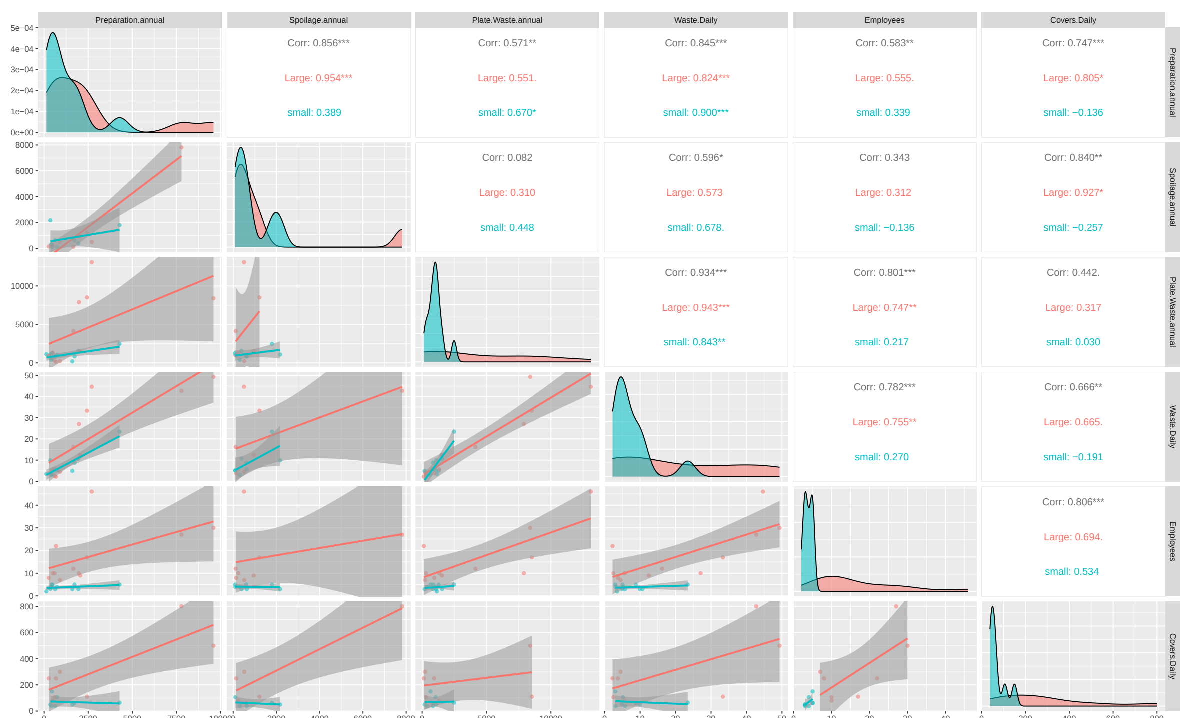

Figure 5: Pairs plot of cafe data coloured by employee size

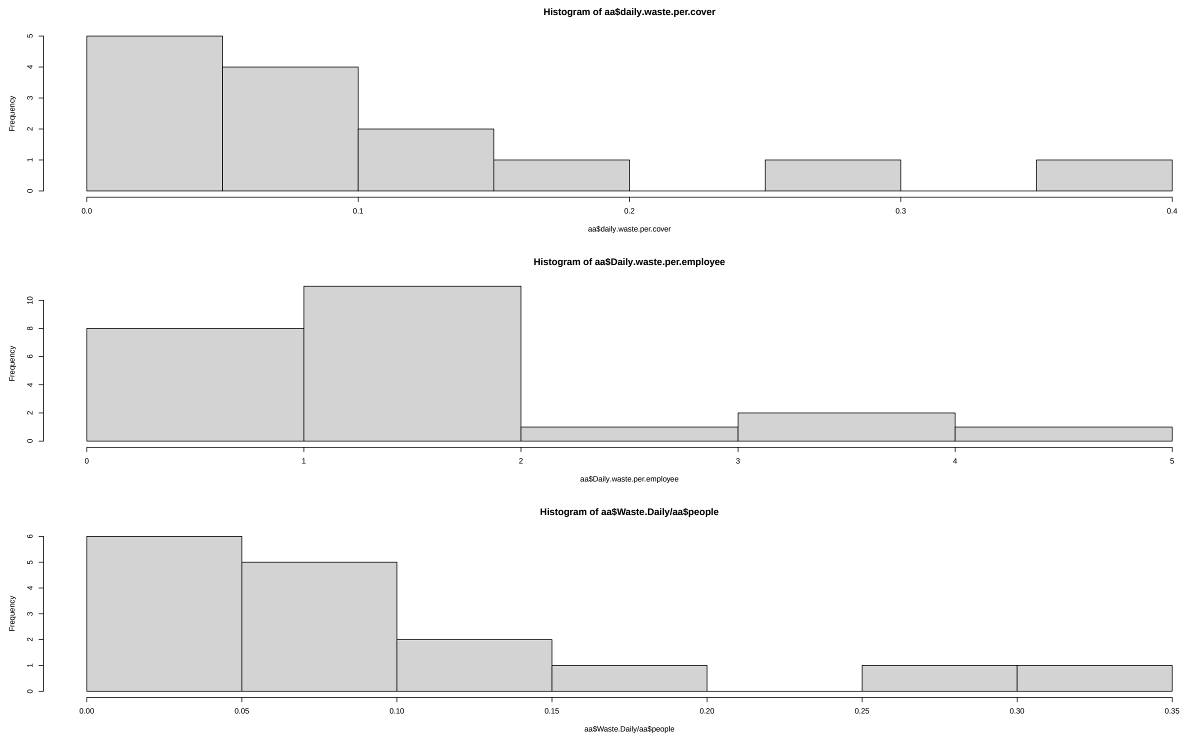

Figure 6: Histograms are presented to visually represent the distribution characteristics of key metrics of foodwaste in cafe

- **Summary Statistics:**
  - The analysis culminates with the presentation of summary statistics, encapsulating key insights and providing a concise overview of the dataset's characteristics.

Table 5: Summary Statistics of key parameters of food waste from cafe data

Variable	N	Mean	Std. Dev.	Min	Pctl. 25	Pctl. 75	Max
Preparation annual	23	1907	2378	134	474	2010	9600
Daily Preparation	23	5.2	6.5	0.37	1.3	5.5	26
Spoilage annual	16	1100	1892	92	217	1020	7817
Daily Spoilage	16	3	5.2	0.25	0.6	2.8	21
Plate Waste annual	22	2643	3531	135	706	2250	13100
Daily Plate waste	22	7.2	9.7	0.37	1.9	6.2	36
Employees	23	11	11	2	4	11	46
Covers Daily	16	185	206	38	58	250	800
Waste Daily	23	14	15	2.2	4.1	20	49
Daily waste per employee	23	1.6	1.1	0.1	0.71	1.8	4.7
daily waste per cover	14	0.11	0.11	0.01	0.028	0.15	0.36
prep per cover	14	0.044	0.048	0	0.013	0.057	0.18
spoilage per cover	10	0.033	0.039	0	0.0025	0.037	0.12
plate waste per cover	14	0.048	0.055	0	0.01	0.057	0.21
sizer	23						
... Large	12	52%					
... small	11	48%					
people	16	195	214	42	62	262	827

2.5.3 Analysis of Hotels and Restaurants data

The analytical approach demonstrated for the cafe data can be seamlessly replicated for other sectors within the hospitality industry, such as restaurants and hotels. The foundational steps, including data import, linear regression modeling, additional regression analyses, and visualization techniques, serve as a versatile framework applicable to diverse datasets representing various establishments.

In the context of restaurants, similar linear regression models can be employed to investigate the relationships between daily waste and relevant factors like the number of employees, daily covers, or both. The extension of the analysis to explore metrics like daily waste per employee and daily waste per cover remains pertinent, providing valuable insights into the unique dynamics of restaurant operations.

Likewise, for hotels, the same structured approach can be implemented to examine patterns and relationships within their waste data. The segmentation of data based on specific characteristics, such as the size of the establishment or other relevant factors, can reveal nuanced insights. Visualizations like pairs plots and scatter plots, with adjustments for the unique attributes of hotels, contribute to a comprehensive understanding of waste generation dynamics.

This adaptable framework ensures that the analytical toolkit developed for cafes can be easily transferred to other sectors, facilitating a consistent and standardized approach to waste analysis within the broader hospitality industry. The versatility of the code allows stakeholders to gain insights into sector-specific waste patterns, aiding in informed decision-making and sustainable waste management practices across various hospitality establishments.

2.6 What-if scenario tool

We created an innovative tool which provides an overview by estimating the annual tonnage of waste generated from designated sectors. Built upon the assumption that the number of meals represents our current best estimate, albeit presently static, the tool empowers users to dynamically adjust per-meal wastage within specific sectors. This flexible and interactive approach allows for a nuanced exploration of potential scenarios, fostering a more adaptable and informed understanding of waste dynamics within diverse sectors.

Objectives:

- Simulate the total food waste by incorporating variations in per-plate waste estimates.
- Illustrate the relative impact of distinct sectors on overall food waste.
- Provide insights into the distribution and range of estimated food waste across sectors.

This endeavor seeks to utilize simulation techniques to understand the potential fluctuations in total food waste by manipulating per-plate waste estimates. By doing so, it aims to highlight the varying impacts of different sectors on the overall landscape of food waste, offering a nuanced perspective on the distribution and range of estimated waste within and across these sectors.

2.6.1 Overview

- estimates per-year tonnage of waste from specified sectors
- assumes number of meals is our best current estimate, currently static
- user can adjust per-meal wastage by sector

The implemented functionalities can be outlined as follows:

1. For each sector, a dedicated function is in place to generate a simulated estimate of the total waste per year. This estimation is contingent upon the mean per-meal waste within that particular sector. Importantly, the flexibility of these functions allows the modeler to choose from a variety of distributions based on their preferences. Currently, the system is configured to employ normal distributions, but this choice can be easily adapted to other distributions as needed.
2. In a broader operational context, the code has been designed to generate a specified number of simulations, denoted as `samples`, representing the annual waste in metric tonnes. These simulations are then aggregated, providing a consolidated view of the overall annual waste across all sectors. This approach facilitates a comprehensive analysis of potential variations and patterns in annual waste outputs, enhancing the tool's utility in exploring diverse scenarios and understanding the broader implications of different per-meal waste scenarios across various sectors.
3. The user has the flexibility to modify per-plate waste settings for individual sectors, facilitating the rerunning of simulations and the examination of the cumulative impact on the outcomes.

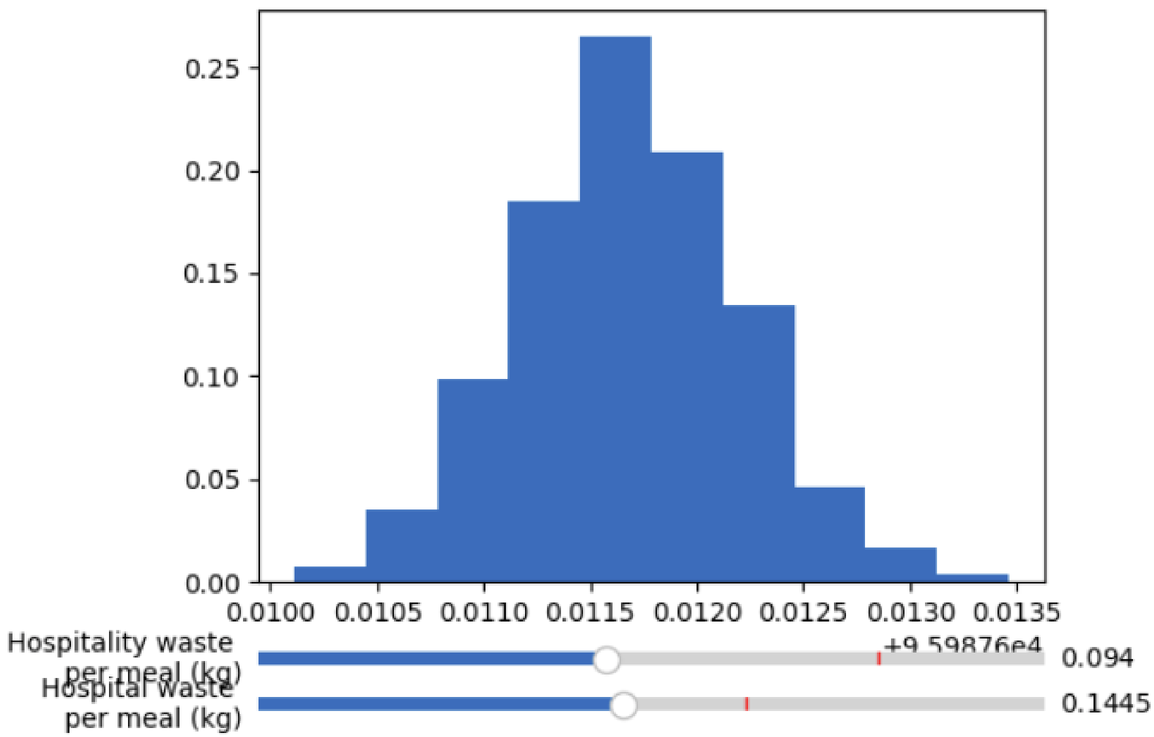

Figure 7: Histogram of these wastage numbers from a Whatif scenario

2.6.2 Limitations

The existing code is subject to several limitations, each requiring specific attention for improvement. Firstly, there are identified issues related to display problems that need to be addressed and rectified. Secondly, the necessity arises to establish source parameters in the code, ensuring proper linkages for a more cohesive and interconnected structure. Lastly, an expansion of the code's functionality involves the addition of another sector, necessitating careful integration into the current framework. These outlined tasks collectively contribute to enhancing the overall robustness and versatility of the codebase.

2.7 Future Work

1. **Exploration of Additional Factors:** Given the nuanced findings regarding daily waste per employee, future work could focus on identifying and incorporating additional factors that may influence this metric. Factors such as menu complexity, seasonal variations, or specific kitchen practices may contribute to the observed independence. A more comprehensive exploration of these variables could provide a holistic understanding of the determinants of food waste per employee, enabling refined and targeted waste reduction strategies.

2. **Temporal Analysis and Trends:** Conducting a temporal analysis to investigate trends in daily waste and its components over time could offer valuable insights. Examining whether the observed dependencies and independencies hold consistently over different time periods, seasons, or special events may reveal dynamic patterns. This temporal dimension can inform strategies for adapting waste management practices to changing circumstances, fostering a more adaptive and responsive approach.

3. **Customer Behavior and Engagement:** Understanding the role of customer behavior in waste generation is crucial. Future work could explore how customer preferences, ordering patterns, and engagement with menu items impact daily waste per cover. Implementing surveys, feedback mechanisms, or analyzing transaction data could provide valuable information on customer choices and their influence on food waste. Incorporating this aspect into the analysis may guide interventions that address both operational and customer-driven factors to enhance overall waste reduction efforts.

4. **Additional Data Collection for Holistic Insight:** Future research could involve comprehensive data collection efforts to capture a broader spectrum of variables that may influence waste dynamics in cafes. This could include detailed information on specific menu

items, ingredient usage, storage practices, and kitchen workflows. Additionally, collecting data on customer feedback, satisfaction, and ordering habits could provide a more nuanced understanding of the customer-side dynamics impacting waste. Integrating such comprehensive datasets will enrich the analysis, offering a holistic perspective on the multifaceted factors contributing to food waste in cafes. This approach aligns with the idea that a more detailed dataset can lead to more accurate models and actionable insights for sustainable waste management strategies.

5. **Development of a Comprehensive What-if Tool with Decision Support:** To enhance the analytical capabilities, future work could involve the development of a more complex What-if tool. This tool could incorporate decision support functionalities, allowing stakeholders to simulate various scenarios based on the identified factors. Integrating decision support tools would provide a more interactive and dynamic platform for exploring potential interventions and assessing their impact on waste reduction strategies in cafes.

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3 Foliar Spray

3.1 Introduction

This challenge focused on foliar plant spray, which involves applying crop protection products (CPPs) directly to a plant's leaves as opposed to putting it in the soil. Foliar spray quality (droplet size distribution, spray volume, spatial distance and number of droplets and concentration of the CPP) can have a huge impact on the performance of the CPP and subsequently the growth, yield and quality of the crop. The question "which spray quality leads to the most efficient CPP performance" is yet to be addressed.

The group discussion started with a Q and A, motivated by Anke's presentation:

(a) Q: How does pesticide act? Is it that the caterpillar needs to have a certain # mg of the substance in it's body? A: Not well known, but this is in line with their hypothesis

(b) Q: do the caterpillars have to take onboard the pesticide while it is in wet form, or is it also taking stuff in when it's dried on a leaf? A:Liquid quickly evaporates leaving behind insecticide.

(c) Q: How often is the pesticide sprayed? and what is it's half A: weekly intervals. (1week later - spray new leaves). Stable on this timescale. Lifetime of caterpillar ~2 days. Want pesticide to kill caterpillar in 10 hrs. 1 sq mm per hour feeding rate.

(d) What's the contact angle for the liquid? ANS: lower than water. Sometimes have super spreader molecules (sometime ST very low). They get coffee-ring effect.

Some initial comments about the caterpillar modelling: The caterpillars eats in an area and defecates, then they proceed to move to another area and repeat the process. In experiments, we will look at one caterpillar per leaf. In general, caterpillars try to separate well from their peers. The initial approach was to make a model with generic parameters for them to test out how caterpillar behaves. Another point worth mentioning is that ingestion is not the only route for absorption of the pesticide but absorption through the feet can be much faster than ingestion.

Some questions that were aimed to be answered in the study group are the following:

- How the spray averages out over the leaves sprayed (space and time).
- How the caterpillar uptake averages out over the leaves (space and time).

- How this impacts on the life cycle of the caterpillar.
- How the leaves sprayed depend on the field geometry and the spraying schedule.
- How does the probability a caterpillar dies depend on (i) the level of the dose on the leaf - may be there is a phase transition with a rapid change in probability depending on the droplet concentration (ii) time on the leaf

There is a nice contrast here between a continuum model, which looks at an average density of insecticide per leaf, and a discrete approach which looks at the number of droplets per leaf. (The second could be tackled using techniques from geometric probability theory)

Assumptions, definitions and parameters for modelling

4'335 (+/- 1'338) **μm larval length**

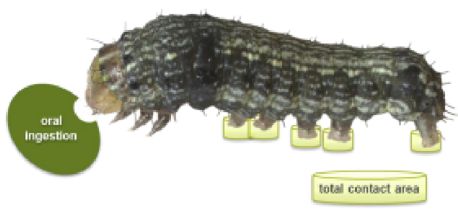
total area abdominal prolegs
189'130 (+/- 90'649) **μm²**

42 (±2) **h life span** of larval stage (L3)

3'957 (±1'021) mm total path length (L3)

94 (±22) mm path per hour (L3)

leaf consumption
13.7 (±2.4) **mm² per hour** (L3)



oral absorption	contact absorption
mouth dimension is unchanged (fixed larval stage)	**constant contact area** (fixed size of prolegs, i.e. larval growth is ignored)
consistent feeding activity (i.e. no resting phase, larval growth is ignored)	**consistent movement activity** (no resting phase)
consistent uptake into larval body (elimination by defaecation is ignored)	droplet size has no impact on diffusion (potential crystallisation related to concentration is ignored)
consistent AI absorption into haemolymph from diet (no gut barrier considered)	droplet size & shape is related to volume (i.e. potential formulation effect such as spreading is ignored)
	constant temperature (24 °C)
chemical stability (no degradation of insecticide on leaf) and consistent exposure on leaf (i.e. potential absorption in leaf waxes, foliar penetration has no impact)	
internal distribution of AI within larva (reaching the target site) is ignored / equal for both absorption routes	
metabolic processes by larva are ignored / equal for both absorption routes	
toxicodynamics of insecticide is ignored (no sublethal effects such as reduced feeding activity and/or movement)	
relative fastest and highest AI uptake into larva leads to maximum effect	

Figure 8: This image shows the assumptions on the pesticide absorption by the caterpillar. The two main methods of absorption, oral and contact absorption are detailed on a table. Anatomical dimensions of the caterpillar are included on the image. The image is taken from the introductory presentation given by Anke Buchholz, Syngenta.

Caterpillar gut/surface absorption model

Consider Figure 8 which shows a simple compartmental model of pesticide absorption via the gut and feet surface pathways. Ideally, we wish to maximise the concentration of the pesticide in the tissue in order to kill the caterpillar. We thus need to consider which is the most effective route, either via ingestion or surface contact, which leads to the highest concentration in the tissue in the shortest amount of time. The concentration of the pesticide in the gut $G(t)$ [μg AI/ mg wwt], blood $B(t)$ [μg AI/ mg wwt], and tissue $T(t)$ [μg AI/ mg wwt] are described by

$$\frac{dG}{dt} = \alpha(t) - (k_1 + k_2)G, \tag{5}$$

$$\frac{dB}{dt} = k_1 V_{GB} G - k_3 B + \lambda \cdot \begin{cases} \phi(t) - B, \text{ if } \phi(t) \geq B, \\ 0, \text{ if } \phi(t) < B, \end{cases} \tag{6}$$

$$\frac{dT}{dt} = k_2 V_{GT} G + k_3 V_{BT} B - \beta T, \tag{7}$$

with the initial conditions

$$G(0) = 0 \quad B(0) = 0 \quad \text{and} \quad T(0) = 0,$$

where V_{GB} is the gut to blood compartmental volume ratio, V_{GT} is the gut to tissue and V_{BT} is the blood to tissue and β is the elimination rate constant. We also observe that the eating rate $\alpha(t)$, and the rate of adsorption through the feet, $\lambda(\phi(t) - B)$, are scaled with respect to the volumes of the gut and blood, respectively. For simplicity we set the volume ratios to unity to begin with.

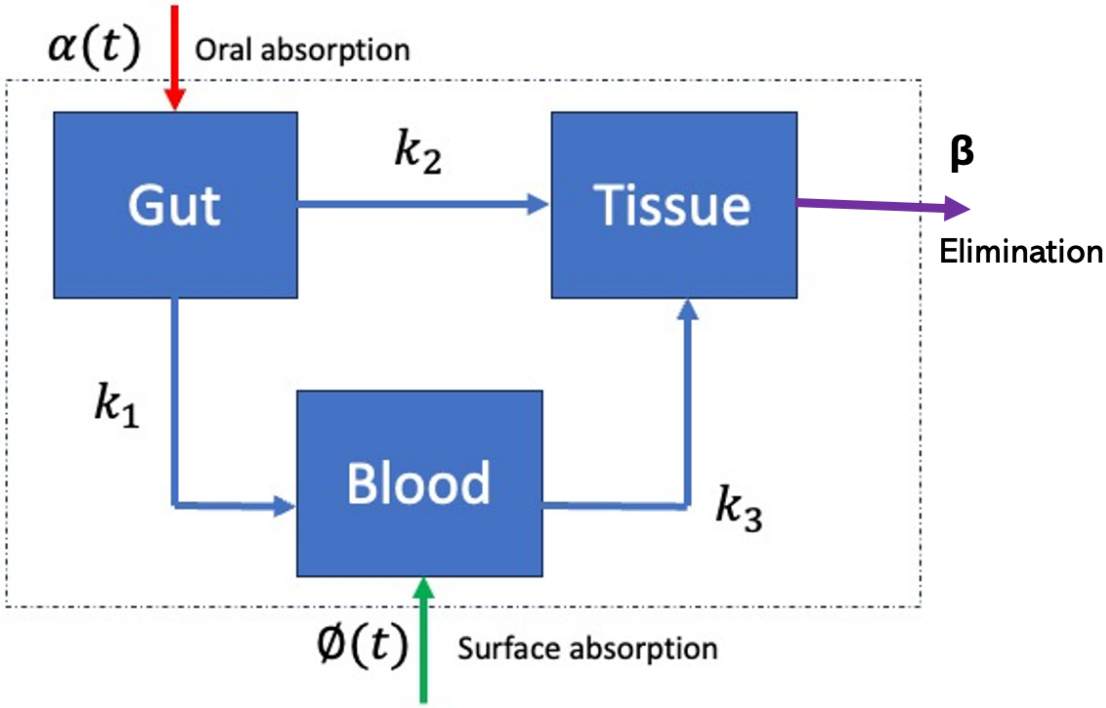


Figure 9: Diagram showing the two absorption processes, dictated by the absorption rates $\alpha(t)$ and $\phi(t)$ and the parameters k_1, k_2 and k_3, which regulate the transmission rates between gut, blood and tissues.

The definitions of the absorption rates $\alpha(t)$ and $\phi(t)$ are the following:

$$\alpha(t) = \frac{\text{Leaf consumption} \times \text{Active Ingredient} \times e^{-\delta t} \times (t - \lfloor t \rfloor)}{\text{Spray Volume}}$$

$$\phi(t) = \left(\frac{\text{Leaf consumption} \times e^{-\delta t}}{\text{Size of one bite}} + \frac{\text{Path}}{\text{Larva Length}} \right)$$
$$\times \left(\frac{\text{Total area abdominal prolegs} \times \text{Active Ingredient} \times (t - \lfloor t \rfloor)}{\text{Spray Volume}} \right)$$

where δ is the decay parameter which can be optimized by fitting the larval movement and toxicity data(Presentation Slides: Page 18). The first term of $\phi(t)$ includes the absorption when the caterpillar is feeding or resting, however the second term includes the absorption when the caterpillar is moving. By changing the values of Active Ingredient (AI) and Spray Volume we can predict the toxicity and hence find the optimized values for AI and spray volume. We can replace $e^{-\delta t}$ with other functions by considering the behaviour of the leave damage. In case of the conversion of the units we include the factor 10^r in the terms , where r is to be determined.

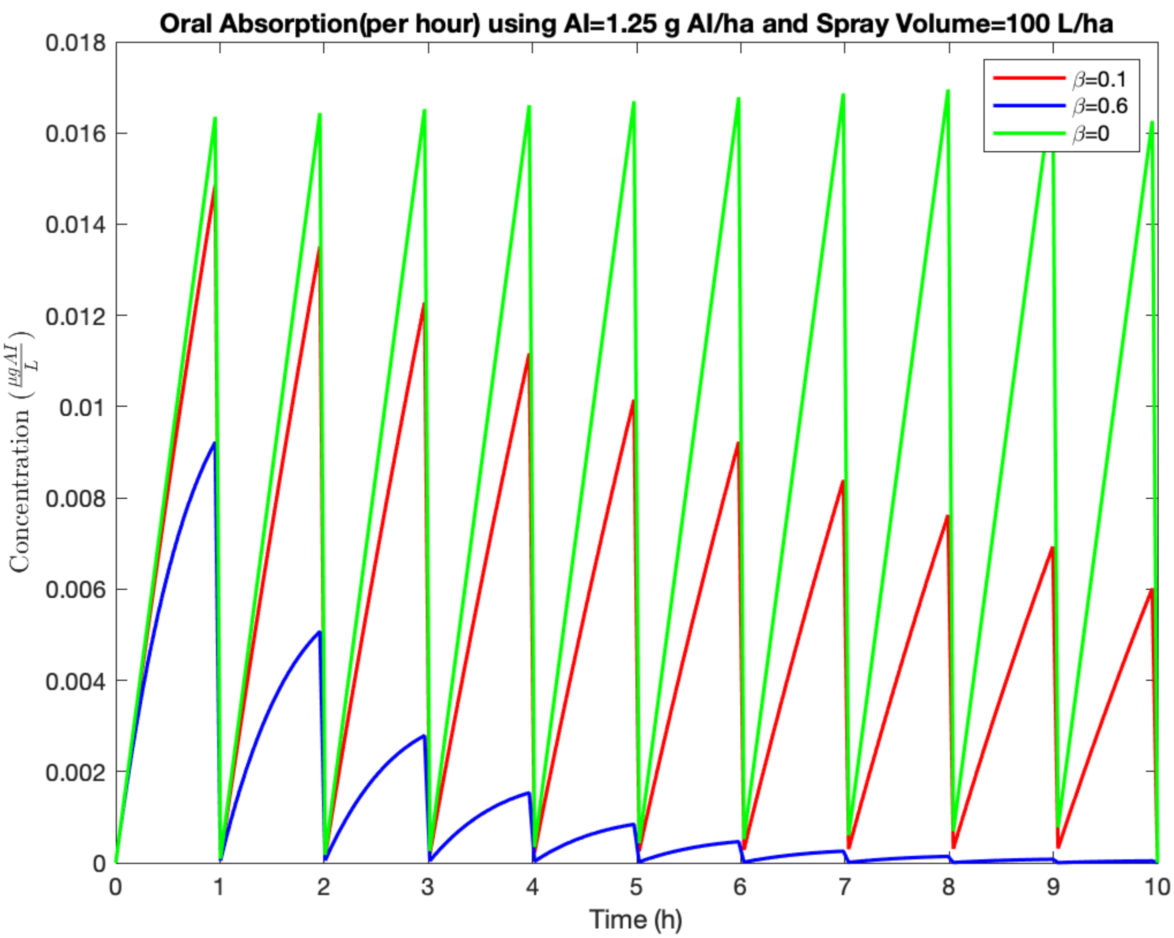


Figure 10: Oral Absorption

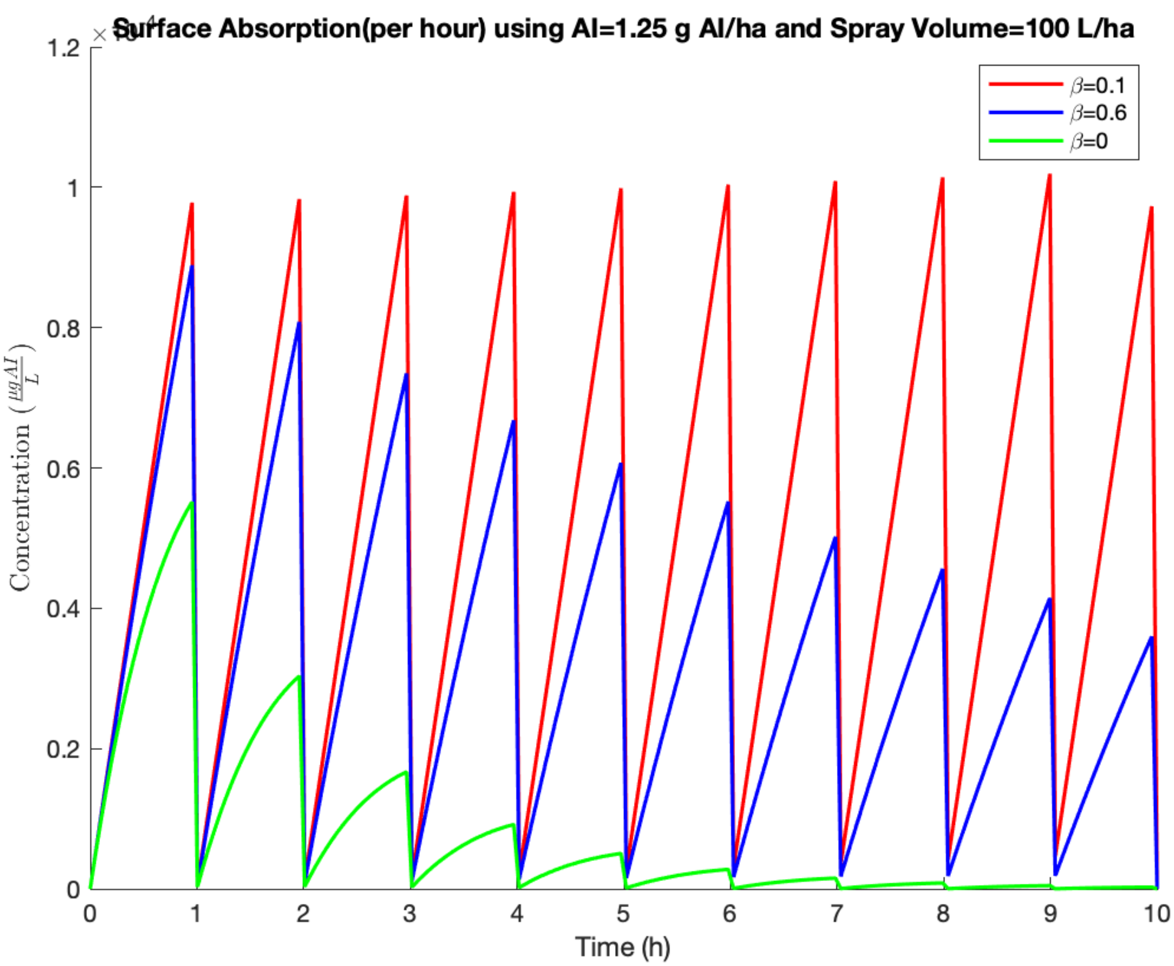


Figure 11: Surface Absorption

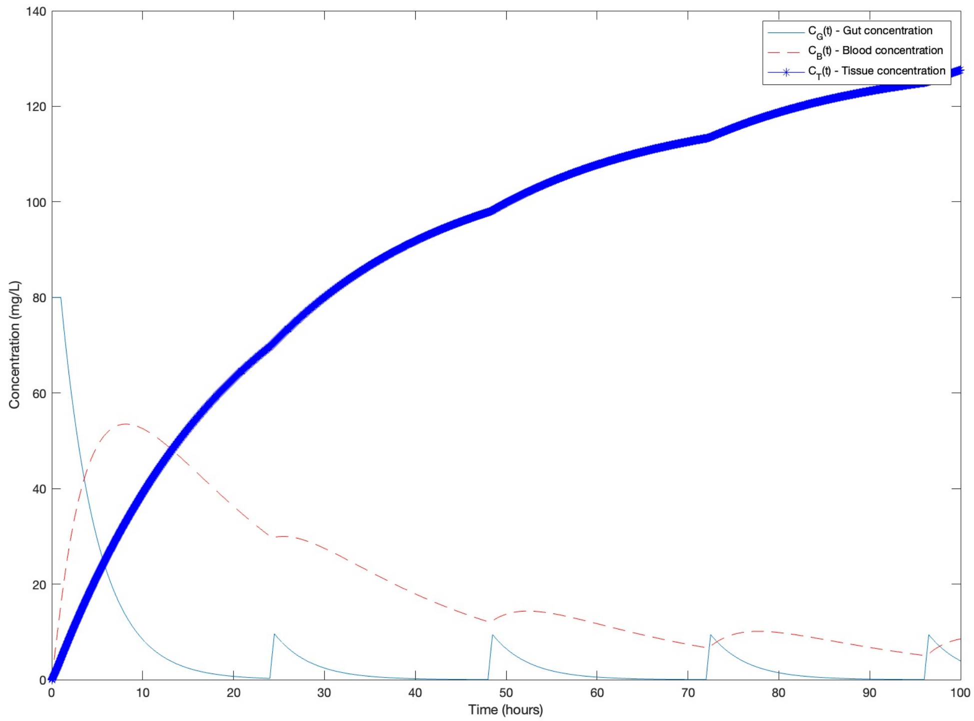


Figure 12: Cat-sim

3.1.1 Parameter estimation

The units of the set of variables are the following: $\alpha(t)$: [μg AI/ h mg wwt] k_1, k_2, k_3: [1/h] λ: [1/h] β: [1/h]

We consider the simplest case first - a constant coverage of AI on leaf (i.e. not discrete spots), and the caterpillar continously moves (i.e. does not stop). For α, we take two things into account: 1.25 [g AI/ha] (application rate) and 13.7 [mmˆ2/h] (leaf consumption).

Therefore, $\alpha = 1.25\left[\frac{gAI}{ha}\right] \cdot 10^6 \left[\frac{\mu gAI}{gAI}\right] \cdot 10^{-10}\left[\frac{ha}{mm^2}\right] \cdot 13.7\left[\frac{mm^2}{h}\right] = 0.0017125\left[\frac{\mu gAI}{h}\right]$.

It's worth highlighting we start with $\beta = 0$

To tackle the set of differential equations given the conditions above, we opted for a metapopulation model:

$$\frac{dG_i}{dt} = \alpha_i(t) - (k_1 + k_2)G_i - \sum_{j=1}^{N} M_{ji}G_i + \sum_{j=1}^{N} M_{ij}G_j,$$
$$\frac{dB_i}{dt} = k_1 V_{GB} G_i - k_3 B_i + \lambda_i(\phi_i(t) - B_i) - \sum_{j=1}^{N} M_{ji}B_i + \sum_{j=1}^{N} M_{ij}B_j,$$
$$\frac{dT_i}{dt} = k_2 V_{GT} G_i + k_3 V_{BT} B_i - \beta_i T_i - \sum_{j=1}^{N} M_{ji}T_i + \sum_{j=1}^{N} M_{ij}T_j,$$

where M_{ji} is migration rate from patch j to i which will still follow the simulation rules.

3.2 Agent-Based Model

The description of the Agent-Based Model (ABM) is the following. There is a caterpillar per leaf, with th leaf divided into x evenly sized grid squares. The initial distribution of droplets is assumed to be uniform.

As the aim of this challenge is to optimise pesticide us, we are interested in modelling different number and concentration of droplets, and their impact on caterpillar survival. We will consider that the caterpillar starts in a random patch of leaf and consumes leaf matter at constant rate. Ingestion of pesticide occurs with rate proportional to consumption rate and the pesticide quantity. As the caterpillar moves across patches, the pesticide absorbed through movement is at a rate proportional to the intrinsic absortion index and the pesticide quantity on the patch. As time progresses and the caterpillar feeds, the pesticide accumulates in the caterpillar and when toxicity levels reach a threshold value, the caterpillar dies. Defecation occurs at rate proportional to consumption in previous timestep.

3.3 Stochastic Gillespie Algorithm

Basic idea behind simulation framework:

- All possible events have an event rate $E_i(t)$. The total event rate is the sum of all possible events, $E(t)$.
- At the beginning of each time step, the next event rate is $N(t) = E(t) * U(0,1)$, where $U(0,1)$ is a uniform random number.
- We then loop through each event and accumulate a partial rate $P(t)$ until $E_{i-1}(t) < P(t) \leq E_i(t)$, and then event i occurs.

- Event rates are recalculated and the process repeats until some criteria met.

Simulation rules At every timestep of the simulation, the caterpillar can either stay where it is, or move to one of its neighbouring patches.

Its propensity to move to a specific patch is dependent on the quantity of food in that patch (denoted by colour of grid square in simulation), negatively weighted by the number of fecal pellets on that patch.

$$M_i(t) = c * Q_{l,i}(t)/N_{f,i}(t),$$

where $M_i(t)$ is the movement rate to patch i (implicit assumption is that caterpillar can move to patch i), $Q_{l,i}(t)$ is the quantity of food on patch i at time t, $N_{f,i}(t)$ is the number of fecal pellets on patch i at time t, and c is a constant.

On the caterpillar's patch it will consume $E(t) = a * Q_{l,i}(t)$ leaf matter, where a is the intrinsic consumption rate.

At the beginning of each time step, the caterpillar will excrete $b * E(t-1)$ onto its current patch before it moves on (or stays on current patch).

Toy netlogo code

Current model implementation

- Code below generates leaf patches, green being free of pesticide, and pink containing pesticide. At the moment there's a fixed number of pink patches randomly distributed and have a fixed pesticide quantity (default value of 1).
- Single caterpillar spawns on random patch and on each tick of the simulation will move to one of its neighbouring patches and consumes the food on that patch. For simplicity, at the moment if there are no patches surrounding it that it can eat from, then it will face the direction of a green patch and move one patch in that direction. We also assume that the caterpillar can move through empty spaces... potentially fine for petri dish model but would need refinement for more realistic field models.
- Consumption increases its satiation by 1, and once the caterpillar reaches a satiation threshold, then it stops eating. It continues moving at each tick, and at each tick its satiation will drop. Once the caterpillar's satiation reaches 0, it can begin eating again.

- If the caterpillar consumes a patch with pesticide on it, then it ingests the pesticide. Once the pesticide levels in the caterpillar reaches a critical value, it dies and the simulation stops.

Some features to implement in the future are:

- Absorption of pesticide through movement.
- Defecation and preferential movement towards patches that are “clean”.
- Identifying suitable parameter values for absorption rate and ingestion rate, satiation thresholds, and critical pesticide levels before death.
- Including droplet dynamics. Incorporation of concentration of drops and size (in terms of the number of patches in an area that represent a single droplet).
- General improvement of visual environment scales (we want each patch in the model to represent a single potential bite for the caterpillar).

3.4 Conclusions

Throughout the study group, great advances were made in the understanding of the interaction between the pesticide and the caterpillars. A set of differential equations which describes how the pesticide is absorbed and transmitted throughout the caterpillar was identified. A simulation which shows the behaviour of the caterpillar was built. Several features that could make the simulation more accurate to the caterpillars behaviour were identified. Finally, the current model allows us to investigate how modifying several variables, such as the active ingredient concentration, would affect the caterpillar. The work done in this brings us a further step closer to answer the question on what is the optimal way to use pesticides.

3.4.1 Next Steps

It would be ideal to combine the ABM model and the dose models, as the ABM model describes what the caterpillar is doing and the dose model reflects how much insecticide is absorbed. The first step would be thinking about how the various parameters in the model, such as the overall dose level of the insecticide on the leaf, aeffect caterpillar death. Another idea would

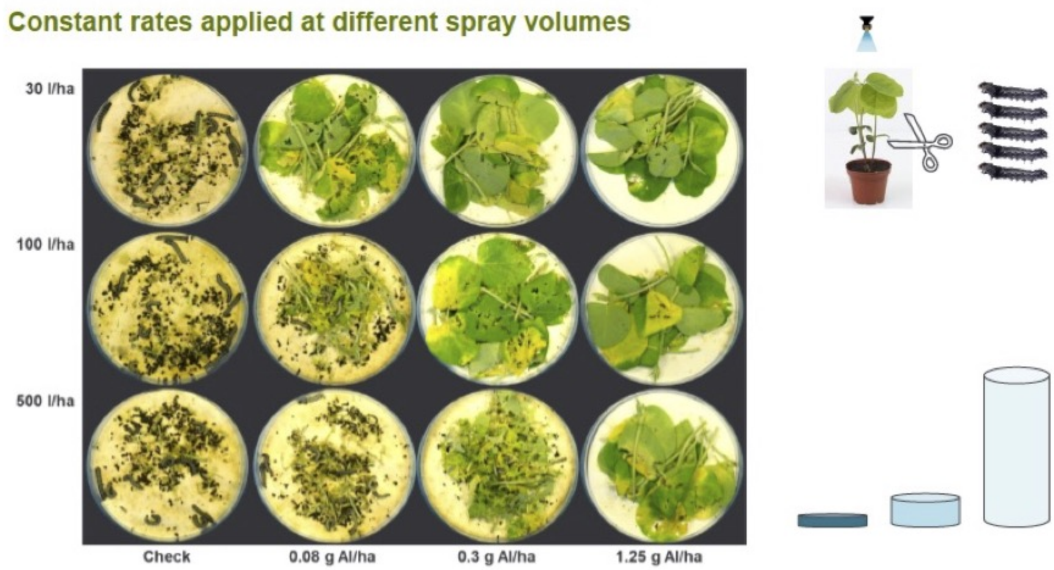


Figure 13: Figure showing a set of 12 petri dishes, each of them containing a specific combination of pesticide amount and active ingredient concentration. This results in different consumption levels of the leaves. Figure taken from n from the introductory presentation given by Anke Buchholz, Syngenta.

be to then reproduce the experimental results (Figure 13), number of caterpillar deaths as a function of the two dosage parameters, in our model. Finally, to identify how to scale up to a field level calculation from this leaf level calculation.

4 CEA Hvac System

4.1 Introduction

This challenge focuses on a vertical farm or controlled environment agriculture (CEA) heating ventilation and air condition (hvac) system. The aim is to devise a control system to maintain target temperature, relative humidity and vapour pressure deficit within the chamber while using the minimum amount of energy. All of the target factors affect each other so changing one changes the others. In addition to this, methods of control affect multiple target factors in different ways. This leads to a complex multivariate system with multiple target parameters and multiple interlinked control methods.

4.2 The Hvac System

The hvac system is heated and cooled by opening and closing vents and varying the operation of heat exchanger grates. For example, to reduce the temperature, either the cooling grate (see Fig. 14) can be used, or the vent employed to increase air flow from outside the system. Humidity can also be controlled either by pumping in fresh air to displace the higher humidity air. Humidity can alternatively be reduced by reducing the temperature – if the temperature is lowered below the dew point condensation will occur to remove water vapour from the air. An excess of water can be released through a drain in the base of the unit. The dew point is the atmospheric temperature (varying according to pressure and humidity) below which water droplets begin to condense and dew can form.

Control of the hvac system is currently done by simple proportional integral differential (PID) loops. This is a well established method to control process variables via a feedback and updating mechanism. Once steady state is achieved, targets are generally maintained with good accuracy. Current control protocols hold conditions accurate to 0.2°C. However, the practice is not efficient as there can be large shifts in conditions and responding dynamically to temperature and humidity corrections can lead to high energy costs.

In short, the hvac system is a complex system of few but highly correlated variables, and under the current control regime high levels of power effort are required to maintain equilibrium. Thus control via PID loops, although effective, is not an environmentally sound solution.

Figure 14 illustrates a simple hvac system. It should be assumed that there is a significant amount of plants, lighting and irrigation equipment within the chamber. This causes the tem-

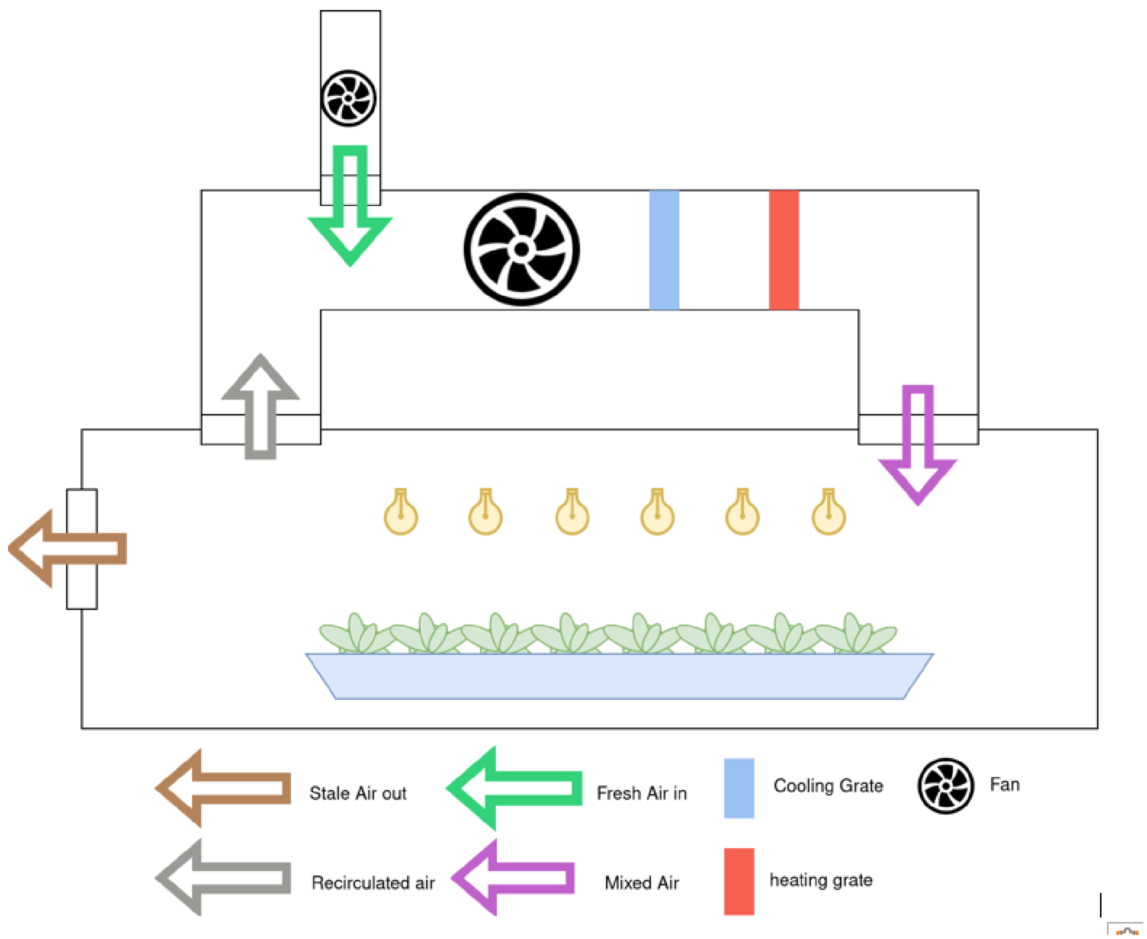
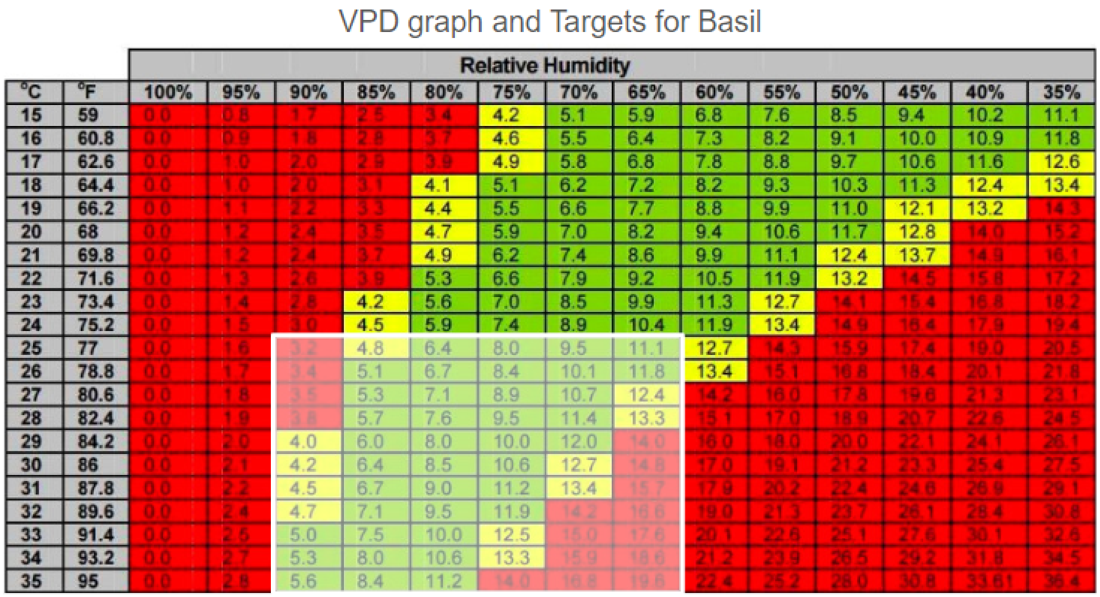


Figure 14: Example of a simple vertical farm or CEA hvac system.



VPD graph and Targets for Basil

		Relative Humidity													
°C	°F	100%	95%	90%	85%	80%	75%	70%	65%	60%	55%	50%	45%	40%	35%
15	59	0.0	0.8	1.7	2.5	3.4	4.2	5.1	5.9	6.8	7.6	8.5	9.4	10.2	11.1
16	60.8	0.0	0.9	1.8	2.8	3.7	4.6	5.5	6.4	7.3	8.2	9.1	10.0	10.9	11.8
17	62.6	0.0	1.0	2.0	2.9	3.9	4.9	5.8	6.8	7.8	8.8	9.7	10.6	11.6	12.6
18	64.4	0.0	1.0	2.0	3.1	4.1	5.1	6.2	7.2	8.2	9.3	10.3	11.3	12.4	13.4
19	66.2	0.0	1.1	2.2	3.3	4.4	5.5	6.6	7.7	8.8	9.9	11.0	12.1	13.2	14.3
20	68	0.0	1.2	2.4	3.5	4.7	5.9	7.0	8.2	9.4	10.6	11.7	12.8	14.0	15.2
21	69.8	0.0	1.2	2.4	3.7	4.9	6.2	7.4	8.6	9.9	11.1	12.4	13.7	14.9	16.1
22	71.6	0.0	1.3	2.6	3.9	5.3	6.6	7.9	9.2	10.5	11.9	13.2	14.5	15.8	17.2
23	73.4	0.0	1.4	2.8	4.2	5.6	7.0	8.5	9.9	11.3	12.7	14.1	15.4	16.8	18.2
24	75.2	0.0	1.5	3.0	4.5	5.9	7.4	8.9	10.4	11.9	13.4	14.9	16.4	17.9	19.4
25	77	0.0	1.6	3.2	4.8	6.4	8.0	9.5	11.1	12.7	14.3	15.9	17.4	19.0	20.5
26	78.8	0.0	1.7	3.4	5.1	6.7	8.4	10.1	11.8	13.4	15.1	16.8	18.4	20.1	21.8
27	80.6	0.0	1.8	3.5	5.3	7.1	8.9	10.7	12.4	14.2	16.0	17.8	19.6	21.3	23.1
28	82.4	0.0	1.9	3.8	5.7	7.6	9.5	11.4	13.3	15.1	17.0	18.9	20.7	22.6	24.5
29	84.2	0.0	2.0	4.0	6.0	8.0	10.0	12.0	14.0	16.0	18.0	20.0	22.1	24.1	26.1
30	86	0.0	2.1	4.2	6.4	8.5	10.6	12.7	14.8	17.0	19.1	21.2	23.3	25.4	27.5
31	87.8	0.0	2.2	4.5	6.7	9.0	11.2	13.4	15.7	17.9	20.2	22.4	24.6	26.9	29.1
32	89.6	0.0	2.4	4.7	7.1	9.5	11.9	14.2	16.6	19.0	21.3	23.7	26.1	28.4	30.8
33	91.4	0.0	2.5	5.0	7.5	10.0	12.5	15.0	17.6	20.1	22.6	25.1	27.6	30.1	32.6
34	93.2	0.0	2.7	5.3	8.0	10.6	13.3	15.9	18.6	21.2	23.9	26.5	29.2	31.8	34.5
35	95	0.0	2.8	5.6	8.4	11.2	14.0	16.8	19.6	22.4	25.2	28.0	30.8	33.61	36.4

Figure 15: Example chart for growing basil, ideal region highlighted by the white box.

perature to rise and increases the humidity in the air.

4.2.1 Assumptions

Assume the chamber is very well insulated to ensure heat is not gained or lost through walls. We also take the volume and pressure of the room to be constant. It is also noted that equipment, such as lighting, in the room uses energy which ends up as heat. Further, that the crops and the irrigation system generate humidity.

4.3 Aim

To maintain target temperature, T, relative humidity, R (see Fig. 15 for the target zone for growing basil well), and vapour pressure deficit, VPD, within the chamber while using the minimum amount of energy.

4.3.1 Factors at play

First, temperature of the chamber and fresh / outside in air (usually °C).

Second, humidity. Relative humidity (RH) (which can be expressed as a percent) measures concentration of water vapour, but in relation to the temperature of the air. To be specific, it is a measure of the actual amount of water vapour in the air compared to the total amount of vapour that can exist in the air at its current temperature. Absolute humidity (expressed as mass of water vapour per cubic metre of air) is a measure of the actual amount of water vapour (moisture) in the air, regardless of the air's temperature. The higher the amount of water vapour, the higher the absolute humidity.

Also of interest are: The dew point – the temperature the air needs to be cooled to (at constant pressure) in order to achieve a relative humidity (RH) of 100%; The vapour pressure deficit (VPD) is calculated as the difference between the amount of moisture that's actually in the air and the amount of moisture that air could hold at saturation; The energy (J) the energy used to increase or decrease the air temperature using the heating and cooling grates in a given time, e.g. the growing period of the crop.

4.3.2 Controls

Temperature can be controlled by:

- Increasing the cold-water flow through the cooling grate will cause the air temperature to drop.
- Increasing the hot-water flow through the heating grate will cause the air temperature to rise.
- Adding fresh air will either increase or decrease the air temperature depending on the relative air temperature outside.
- Relative humidity can be controlled by:
- Raising the temperature will cause the RH to drop.
- Lowering the temperature will cause RH to increase.
- Reducing the absolute humidity will cause the RH to drop.
- Increase the absolute humidity will cause the RH to increase.
- Absolute humidity can be controlled by:
- Lowering the temperature of the cooling grate to below the dew point of the air leading to condensation. (The heating grate can then be used to raise the air temperature back up to its original temperature).

- Adding fresh air fresh air will either increase or decrease the absolute humidity depending on if the fresh air has a high or lower absolute humidity. The temperature of the mixed air can then be brought up or down as required by using the grates.

- A humidifier can be added to increase humidity but in reality is almost never needed because all of the plants and irrigation systems create a lot of humidity so only a decrease in humidity is required.

4.4 Signal Outputs

Output signals were captured during operation between 13:28 and 22:59 hours, on the 13^{th} March 2023. Signals recorded give the date and time stamp (minutes), target humidity value, average humidity value per minute, effort measured (in Joules) to maintain target humidity value, effort (J) to maintain target temperature value, average temperature value (over a minute) (°C), target temperature value. See Figs. 16 and 17

Plants, like other living organisms, require periods of rest; in figures 18 and 19 fluctuations in humidity and temperature are minimal as are the associated energy efforts. Effort to maintain target temperatures and humidity values is most pronounced during hours of daylight. Overnight, especially pre-dawn, there is very little energy input required to control the system.

4.5 Mathematical Model

In this section we build a direct mathematical model for the operation of an hvac chamber, using basic physical laws. To date, not all the required physical constants have been put into the model, and we have not yet examined its implications for power use/cost.

4.5.1 A sealed chamber

Let T be the temperature in the air and t be time. We first write down a model for what's going on without any controls other than the lights going on and off, the lights being the only source of heat, water vapour gained by the air in the chamber through transpiration and evaporation, and no losses of heat, air or water vapour.

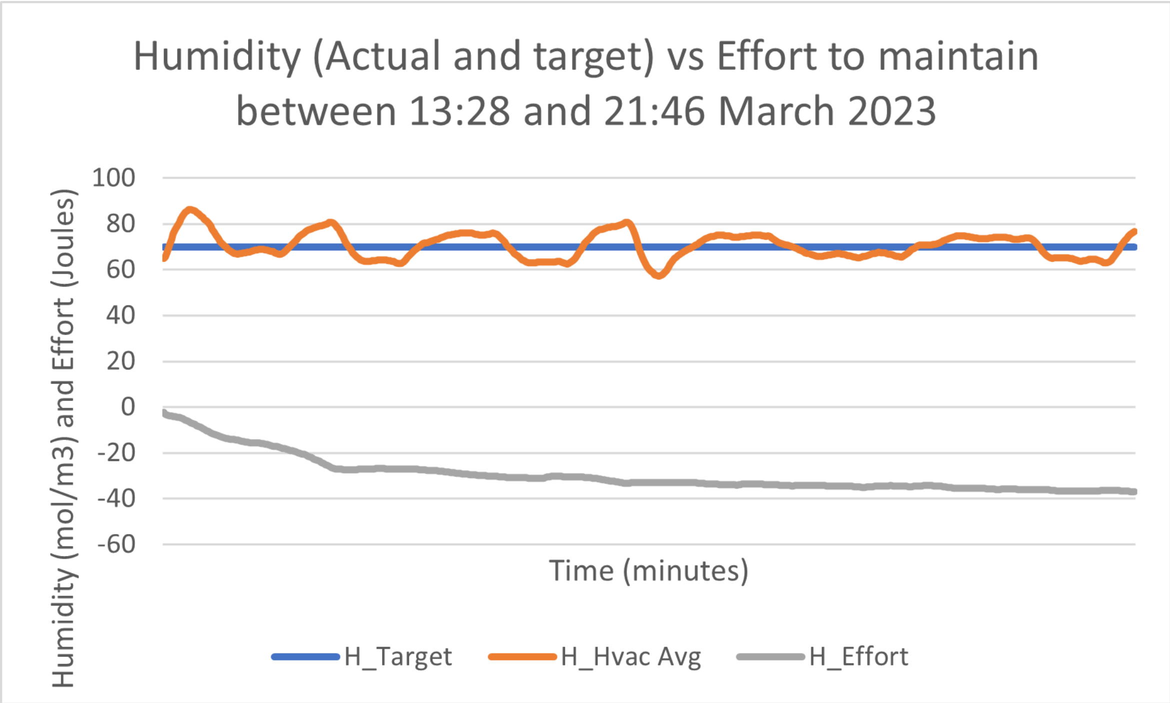


Figure 16: Actual and target humidity against effort to maintain target between 13.28 and 21.46 hrs.

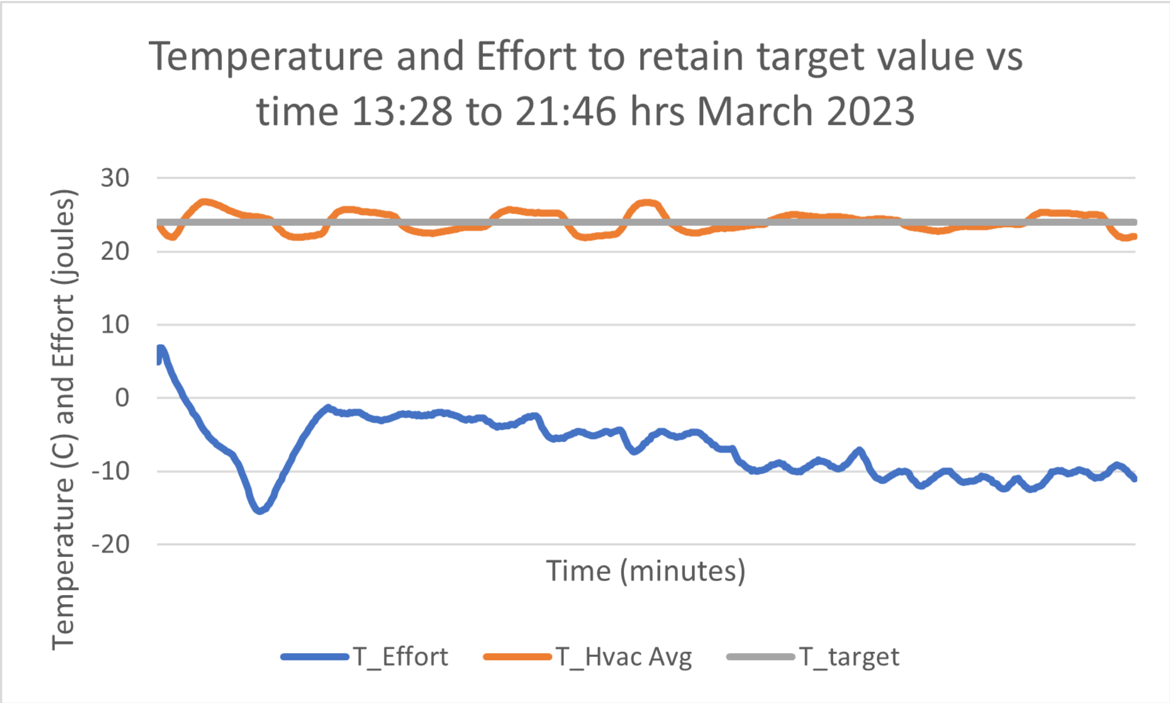


Figure 17: Temperature and effort to retain target values between 13.28 and 21.46 hrs.

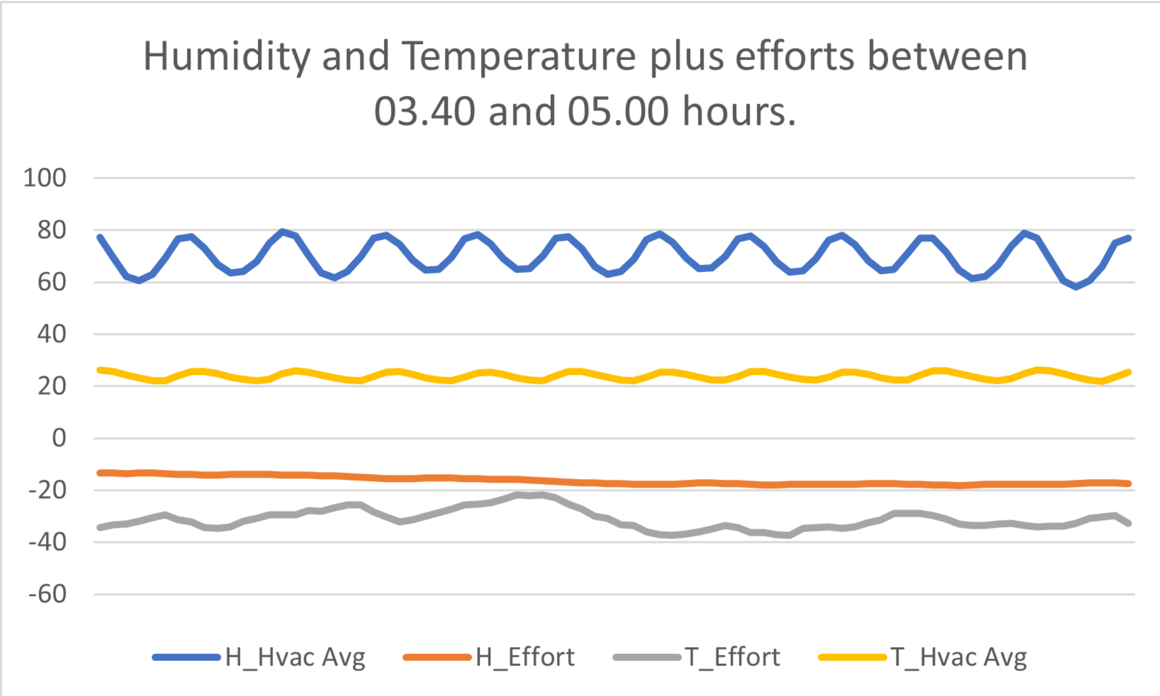


Figure 18: Humidity and Temperature targets energy requirements drop during period 03.40 to 05.00 hours.

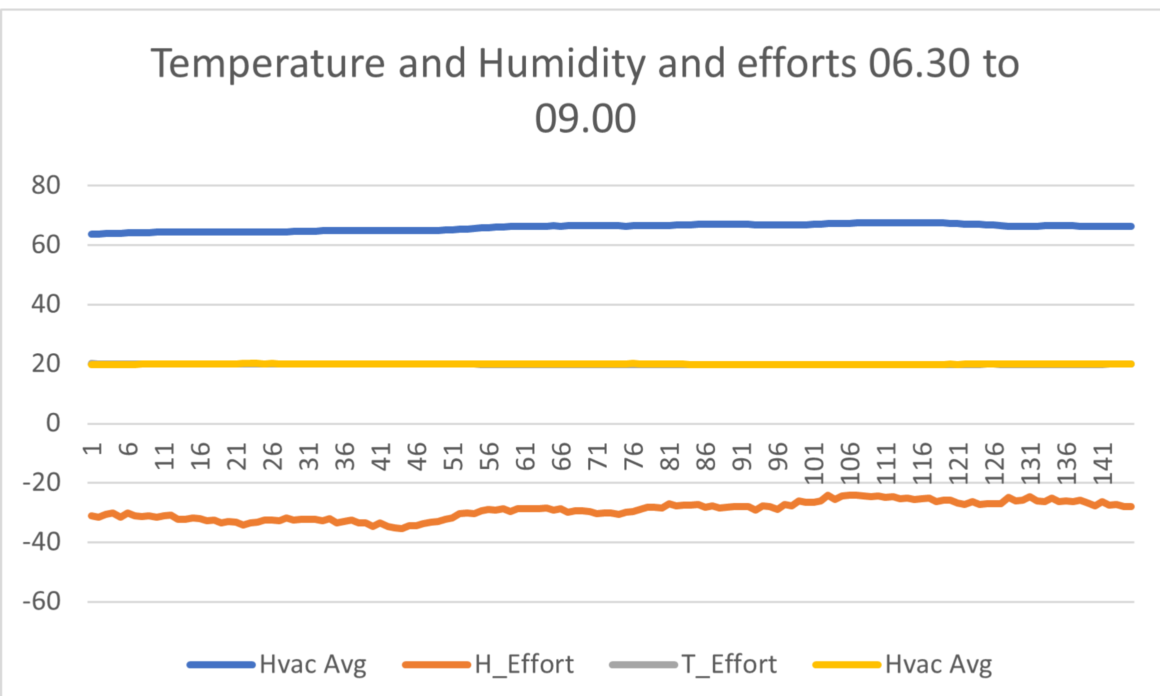


Figure 19: Minimal energy requirements during period 06.30 to 09.00 hrs.

Conservation of heat gives

$$\rho c_v V \frac{\mathrm{d}T}{\mathrm{d}t} = \lambda(t) = \lambda_0(1 + \lambda_1 f(t)),$$

where V is the volume of the room, λ_0 is the rate of energy production when the lights are off and λ_1 is the relative extra rate of energy production when the lights are on, and

$$f(t) = \chi(t; t_1, t_2) = 1 \text{ for } t_1 < t - nt_d < t_2, \text{ with } 0 < t_1 < t_2 < t_d,$$

$$f(t) = 0 \text{ otherwise}, n = \dots, -2, -1, 0, 1, 2, \dots, \text{ and } t_d = \text{ length of a day.}$$

Notes: **1.** We have presently neglected both latent heat and specific heat of the evaporating water. Looking at sizes, the latter seems reasonable, but it appears that latent heat of water vapour can give a contribution of a similar size to heat content as that associated with a temperature change of 20°C of the air. This should then be included in later work.
2. Heat content of soil etc. has also been disregarded. This might need looking at further. Limiting cases which might be easily treated could be soil having small or large heat capacity (relative to the air) and/or heat transfer between air and soil being “fast” or “slow”. Without some simplifying limit, it might be necessary to consider another equation for the variation of soil temperature.
3. The chamber is taken, for the moment, to be completely sealed, so its air mass and the air density ρ are constant, and hence the use of c_v for the specific heat. This presumably is rather unlikely and maintaining atmospheric pressure (approx.) might be expected. With rising temperature (as indicated in this very simple model), there would then be venting and heat loss to the outside world; with a cooling model (right-hand side of the T equation negative), air would be pulled in from the outside. Below, some modelling is done of exchange of heat when there is forced venting, as part of the temperature, and humidity, control mechanism; “natural” venting might also be looked at.

We denote the absolute humidity content by H and the relative humidity by R, given by

$$R = \frac{H}{S(T)},$$

where $S(T) \approx Ce^{\nu T}$ is the saturation level (C and ν are constants), which is the most water vapour that the air can hold at a given temperature. Conservation of water in the air gives:

$$V \frac{\mathrm{d}H}{\mathrm{d}t} = \kappa_s(T, R) + \kappa_P(T, R, f)$$

where

$$\kappa_s(T, R) = A_0(1 + A_1 T)(1 - R)$$

is the supply rate of water due to evaporation from all non-plant surfaces (e.g. soil), which goes up as the temperature goes up and down as the relative humidity goes up (we picked linear for convenience); A_0 and A_1 are constants, and

$$\kappa_p(T, R, f) = A_2(1 + A_3T)(1 - R)(1 + A_4f)$$

NB We could eliminate one of R and H from the equations.

4.5.2 Forced venting

Once there is venting (natural, as remarked on above, or forced, as here), we must be more careful regarding air density etc. Taking air pressure as fixed (no worries about very high/low pressure weather systems!), $p = p_A$, and, on taking the air to behave as an ideal gas, its density, now variable, will be given by $\rho = k_a p_A/T$, where k_a is a constant and using absolute temperature.

We take the introduction of fresh air (green arrow in sketch, Fig. 14), with external temperature T_e and absolute humidity H_e, to have specified volume flow rate Q_I, so the mass flow rate is $\rho_e Q_I$, as the external air to has density $\rho_e = k_a p_A/T_e$. This venting rate Q_I is assumed much less than the recirculation (grey arrow in sketch, Fig. 14) rate, say Q_r (which ensures that the air doesn't suddenly become supersaturated). There is also out-venting (brown arrow in sketch, Fig. 14), with volumetric rate Q_O and mass flow rate $Q_O\rho$. Both Q_I and Q_O are assumed to be positive – they really are in-flow and out-flow, respectively,

To ensure constancy of volume of the chamber, we must have
$Q_O = Q_I - \dfrac{V}{\rho}\dfrac{\mathrm{d}\rho}{\mathrm{d}t}$.

The net rates of change due to venting are now:

of energy (input less output), $c_p(\rho_e Q_I T_e - \rho Q_O T) = c_p k_a p_A(Q_I - Q_O)$;

of mass of air, $\rho_e Q_I - \rho Q_O = k_a p_A(Q_I/T_e - Q_O/T)$;

and of water vapour $Q_I H_e - Q_O H$.

Note the use of c_p for specific heat (instead of c_v) now that fixed pressure is being used. It should also be observed that, through comparing heat and mass contents of the chamber, if venting was the only thing happening, the second and third equation above would give $\mathrm{d}T/\mathrm{d}t > 0$ for $T_e > T$ and < 0 for $T_e < T$, as expected (remember that $Q_I > 0$).

Combining with the earlier equations for a closed chamber (still ignoring latent heat of evaporation and heat capacity of soil), but with c_p replacing c_v and including an equation for mass of air, $V\rho$:

$$c_p V \frac{\mathrm{d}}{\mathrm{d}t}(\rho T) = \lambda(t) + c_p k_a p_A (Q_I - Q_O),$$

$$V\frac{\mathrm{d}\rho}{\mathrm{d}t} = k_a p_A (Q_I/T_e - Q_O/T),$$

$$V\frac{\mathrm{d}H}{\mathrm{d}t} = \kappa_s(T,R) + \kappa_P(T,R,f) + Q_I H_e - Q_O H.$$

The mixed chamber and fresh air, with temperature and humidity approximately those of the chamber, flows from the inlet to the grates, which we must now model.

4.5.3 Heating and cooling grates

To get an idea as to how to model the two heat-exchanging grates, we first consider the hot grate as a counter-flow heat exchanger (although it is not one!). Taking the air to flow with mass flux q_1, to have specific heat c_1, and local temperature T_1, going from $x = 0$ to $x = l$, the water to have corresponding quantities q_2, c_2, and T_2, it going from $x = l$ to $x = 0$, and a heat-exchange coefficient h (J K^{-1} m^{-1}), the temperatures satisfy

$$c_1 q_1 \frac{\partial T_1}{\partial x} = h(T_2 - T_1),$$

$$-c_2 q_2 \frac{\partial T_2}{\partial x} = h(T_2 - T_1).$$

For convenience we partially non-dimensionalise, writing $x = ly$, $\alpha_j = (hl)/(q_j c_j)$ for $j = 1, 2$:

$$T_1{}' = \alpha_1(T_2 - T_1); T_2{}' = \alpha_2(T_2 - T_1);$$

with $'$ = d/dy, and given inlet temperatures $T_1(0) = T_{1i}$ and $T_2(1) = T_{2i}$. Solving these gives (apart from the special case of $\alpha_1 = \alpha_2$) an outlet air temperature of

$$T_{1O} = T_1(1) = \frac{E(1-(\alpha_2/\alpha_1))T_{1i} + (1-E)T_{2i}}{1-(\alpha_2/\alpha_1)E}$$

with $E = \exp(\alpha_2 - \alpha_1)$.

From these we can see that (as should be expected): for α_1 small (air whistling through), $T_{1O} \sim T_{1i}$; for α_1 large (air hardly moving), $T_{1O} \sim T_{2i}$; for α_2 small (lots of heating water, so its temperature remains at T_{2i}), $T_{1O} \sim T_{2i}(1 - \exp(-\alpha_1)) + T_{1i}\exp(-\alpha_1)$; for α_2 large (hardly any heating water), $T_{1O} \sim T_{1i}$.

All these suggest that for the heating grate, the warmed air temperature, T_O, should be related to the incoming air temperature, T_i, by a law of the form

$$T_O = h_h T_h + (1 - h_h)T_i,$$

with T_h the temperature of the heating water (as it comes in), and h_h a coefficient depending upon the flow rates: $h_h \to 0$ for water flow rate going to zero, $h_h \to h^* < 1$ for water flow rate going to infinity. For the present, we might take h_h to vary with the hot-water flow rate as

$$h_h = h^*(1 - \exp(-Q_h/Q_h^*))$$

with $h^* < 1$ and Q_h^* some constant values. N.B. If the hot water is recirculated, given that we want to minimise power use, we might also be interested in the out-put hot-water temperature here, got by conservation of energy, noting that the power taken up the chamber air, and so lost by the hot water water, is $c_p \rho Q_r (T_i - T_O) = c_p \rho Q_r h_h (T_h - T_O)$.

Some extra caution might be demanded given for the constant-pressure case we are considering, as the mass flow rate of air will change with temperature (this possible difficulty would be removed for a "closed" case of constant mass and density). However, as the density changes will not be especially large and, in the present work, we take h_h to be independent of T.

The cold grate might be expected to work in the same sort of way, except for the occurrence of condensation. Looking at a counter-current representation, the same equations as for the hot grate might apply where the air is not saturated with water vapour, and latent heat has to be allowed for where the air is saturated:

$$c_1 q_1 \frac{\partial T_1}{\partial x} = h(T_2 - T_1) \text{ and } H = const. \text{ where } H < R(T_1);$$

$$q_1 \left(c_1 + LS'(T_1)\right) \frac{\partial T_1}{\partial x} = h(T_2 - T_1) \text{ where } H = R(T_1);$$

$$-c_2 q_2 \frac{\partial T_2}{\partial x} = h(T_2 - T_1);$$

H and T_1 are given at $x = 0$, and T_2 at $x = l$. In general this free-boundary problem doesn't have an explicit solution, so, for the present, we proceed as at the final stage of the hot-grate modelling and assume a form of a law for its operation. We then take the cooled air temperature, T_O, to be related to the incoming air temperature, T_i, by a law of the form

$$T_O = h_c T_h + (1 - h_c) T_i + (L/(\rho c_p))(H_i - H_O),$$

$$H_O = S(T_O),$$

so

$$T_O + (L/(\rho c_p)) S(T_O) = h_c T_h + (1 - h_c) T_i + (L/(\rho c_p)) H_i,$$

with T_c the temperature of the cooling water (as it comes in), and h_c a coefficient depending upon the flow rates: $h_c \to 0$ for water flow rate going to zero, $h_c \to 1$ for water flow rate going to infinity. (We might take $h_c = h_h$ if the grates are very similar.) As long as h_c has these expected properties, along with it being increasing with flow rate, we again will have T_O and H_O increasing with H_i and T_i and decreasing with water flow rate – we're assuming that $T_c < T_i$ and that condensation will occur at the grate. For the present, we might again take h_c to vary with the cold-water flow rate as

$$h_h = c^*(1 - \exp(-Q_h/Q_c^*))$$

with $c^* < 1$ and Q_h^* some constant values, despite any effects of water condensation. **The effect of condensed water on heat transfer at the cold grate needs further study.**

N.B. If the cold water is recirculated, given that we want to minimise power use, we might also be interested in the out-put cold-water temperature here, got by conservation of energy, noting that the power lost the chamber air and from the condensed vapour, and so gained by the cold water water, is $c_p\rho Q_r(T_i - T_O) + LQ_r(H_i - H_O) = c_p\rho Q_r h_c(T_i - T_c)$. (The fact that humidity and latent heat do not appear directly in this final expression is another indication that condensation should probably affect h_c.)

Putting the effects of the grates into the model:

The cold grate sees input temperature and humidity (approximately) T and H, so its outputs will be T_i and $H_i = S(T_i)$ given by

$$T_i + (L/(\rho c_p))S(T_i) = h_c T_h + (1 - h_c)T + (L/(\rho c_p))H.$$

These then come into the hot grate which outputs temperature and humidity T_O and $H_O = H_i$, with

$$T_O = h_h T_h + (1 - h_h)T_i.$$

Air with this temperature and humidity (re)enters the chamber, with mass flow rate $Q_r\rho$, while the same flow rate takes air of temperature T and H out. Accounting for the further flow differences we then get

$$c_p V \frac{\mathrm{d}}{\mathrm{d}t}(\rho T) = \lambda(t) + c_p k_a p_A (Q_I - Q_O) + c_p \rho Q_r (T_O - T),$$

$$V \frac{\mathrm{d}\rho}{\mathrm{d}t} = k_a p_A (Q_I/T_e - Q_O/T),$$

$$V \frac{\mathrm{d}H}{\mathrm{d}t} = \kappa_s(T, R) + \kappa_P(T, R, f) + Q_I H_e - Q_O H + Q_r(H_O - H).$$

We still also have $Q_O = Q_I - \frac{V}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}t}$ and $R = H/S(T)$.

4.5.4 Parameters

Some of the physical "constants" in the model(s) are standard:

- Specific heat of air, $c_p = 993$ J kg^{-1} K^{-1};
- Constant relating pressure and temperature of air to its density, $k_a = 3.5 \times 10^{-3}$ kg K m^{-1} N^{-1};
- External pressure, $p_A = 1.01 \times 10^5$ N m^{-2} (might differ according to weather – measured);
- Latent of vaporisation of water, $L = 2.26 \times 10^6$ J kg^{-1};
- Humidity saturation law (approximate, based on being near 30° C, i.e. 303 K, $S \approx 3.04 \times 10^{-2} \exp(0.055$ K$^{-1}(T - 303))$ kg m^{-3};
- Day length $t_d = 24$ hrs $= 8.64 \times 10^4$s.

Some constants should be clearly given by the design and operation of the HVAC chamber:

- Lighting on and off times t_1 and t_2 (s);
- Background heating (on all the time), λ_0 (J s^{-1}), and relative heating due to lighting, λ_1 (dimensionless);
- External humidity (measured during operation), H_e (kg m^{-3});
- Volume of (air in) chamber (neglecting piping?), V (m^3);
- Thermal mass of soil etc. inside chamber (hopefully small compared with that of the air) (J K^{-1});
- Volumetric recirculation rate, Q_r (m^3 s^{-1}).

Other constants might be trickier to estimate:

- Heat transfer coefficient between soil and air (J s^{-1} K^{-1}) – if needed because thermal mass of soil is not small;

- Evaporation-rate coefficients A_0 (kg s^{-1}) and A_1 (K^{-1}) (these might vary with the state of the plant growth);
- Transpiration-rate coefficients A_2 (kg s^{-1}), A_3 (K^{-1}) and A_4 (dimensionless) (these might vary with the state of the plant growth);
- The grate heat-transfer coefficients h^* (dimensionless), Q_h^* (m^3 s^{-1}), c^* (dimensionless) and Q_c^* (m^3 s^{-1}) (the last two assuming the law suggested for the cold grate is reasonable).

For some of these, data fits, with the HVAC chamber in operation, might have to be used, as opposed to applying isolated experiments or using prior knowledge from elsewhere.

4.6 Model Implementation

Description of Model Implementation We implement our HVAC model as a Gymnasium environment. Our Gymnasium environment has an action space, an internal model, and an observation space. Let us discuss these three ingredients one by one.

The action space describes the actions we can do to interact with our environment. In our case, we can dial up/down three pieces of equipment: the venting fan, the heating grate, and the cooling grate. Thus, we model the action by a vector of 3 discrete numbers, each can take a value from 0 to 100 with 0 meaning the equipment is off and 100 meaning the equipment is at max capacity.

The internal model is constructed based on the o.d.e.s presented in the previous section. Here, we simplify our environment by considering discrete time steps. In particular, a time step in our environment corresponds to 1 hour. Note that, besides implementing the o.d.e.s the mathematical models, one also needs to specify many presently undetermined constants. These constants depend on the specific properties of the chamber (e.g., lighting heat, non-light heat, volume of chamber, etc.) and equipment (e.g., max capacity of the venting fan, flow range and water temperature of the heating grate, etc.) that we wish to model.

The observation space describes what we can observe from our environment. With our sensors, we assume that we observe the following:

- Temperature inside the room — modelled by a real number $\in (-100, 100)$
- Temperature outside the room — modelled by a real number $\in (-100, 100)$
- Humidity inside the room — modelled by a real number $\in (-100, 100)$

- Humidity outside the room — modelled by a real number $\in (-100, 100)$
- Energy usage — modelled by a real number $\in (-100, 100)$
- Lights are on or off — modelled by a discrete number $\in 0, 1$ (0 means off, 1 means on)
- Whether the plants are alive — modelled by a discrete number $\in 0, 1$ (0 means dead, 1 means alive)

The way the environment works is that: At time t, we receive a set of observations (temperature etc.). We can then take an action which determines the exact form of the internal model o.d.e.s. I.e., different actions give us a different sets of coefficients for our o.d.e.s. From these o.d.e.s, the internal model will give us the set of observations at the next time step $t + 1$.

Progress update To implement the internal model, we first need to complete our mathematical model. In particular, we need finish three main tasks: (i) model how the chamber physics work using o.d.e.s, (ii) model how turning on/off the equipment modifies said o.d.e.s, (iii) determine constants/coefficients that are characteristics to of our chamber and equipment. As of the time of writing, these are not yet complete, and, as a result, the code implementation of the model is at a preliminary stage only.

4.7 Optimisation

Approach The overall approach is to use Reinforcement Learning (RL) to train an AI to give a suggestion given any environment scenario. Subsequently, we can fine tune the suggestion using evolutionary strategies. The reasoning for using this approach is because it's versatile, easy implement, and generally gives good and consistent suggestion. With more time, other methods (analytic, numerical, or otherwise) should be considered.

Progress update A simple implementation of the optimisation approach above has been done. Nevertheless, as the modelling is not entirely finished, we have not been able evaluate how good our control is yet.

4.8 Further Work

Whilst significant progress has been made in the modelling of the hvac system to date, further work is necessary to produce a reliable alternative to the current control system. In brief:

- System and complexities, e.g. heating and cooling grates, modelled mathematically.
- Further mathematical modelling is required to complete the system representation.
- Some elementary data analysis completed, this should be extended alongside further analysis to model the system behaviours and to extract realistic parameter values necessary to populate the mathematical model.
- Computational model to construct and implement with parameters to be estimated from data.

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