A New Perspective on the Analysis of Vertical Farms: An Exploration of the Potential of an Open-Source Simulation Software Tool to Develop a Framework

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Abstract

This thesis evaluates the various fields that have influenced the development of vertical farms, with a specific focus on the significant gaps that are found in the published literature. It aims to improve our understanding of the concept of vertical farms, bringing together the variety of theories that are attached to this industry.

This work proposes a novel approach to tackle the gap in knowledge related to the area of simulation of vertical farms. Through this investigation it was found that the developed analytical and conceptual framework proposed has significant potential to calculate certain parameters relevant to vertical farms, but it requires further development in order to consider in more detail added important parameters. This study argues that the approach to vertical farming development requires a multifaceted integration of several disciplines and without this integration its deployment is significantly more challenging. The lack of data/knowledge sharing and transparency of information have been hindering the faster development of this industry.

The proposed approach has been developed by scoping the capabilities of HTB2 as a potential software tool to develop a simulation framework. Although novel and positive in many areas, this framework still possesses several limitations, mainly linked to the shortcomings related to the detailing of plants' characteristics. Simulations normally use a series of assumptions and simplifications and this case is not different. Nonetheless, the intrinsic characteristics of plants do require better attention. The limitations discussed in this thesis, suggest clear advisory steps towards developing further studies to be able to take this knowledge on board and move it forward. The software mainly focuses on the energy balance of the vertical farm, calculating for example the energy consumption of lights, ventilation, etc, as well as the relative humidity and other parameters.

The framework is developed by using an estimated base-case scenario and it is thereafter tested with the monitored data of a real case study of a commercial indoor vertical farm, actively producing edible plants and fish

using an aquaponic system, based in London (at the time of this investigation).

Based on the literature found during the lifetime of this project, no other software tools have developed a comparative study such as this one, where results can be obtained to create parallel appraisals between monitored physical vertical farms and simulated representation of the same farms. The work presented here aims to serve as a tool for further development in this area, it humbly accepts that it is not a solution to all the problems faced by vertical farms yet, but it does bring this topic a step closer to finding a robust simulation model in this sector. An important aspect of this research was also affordability and accessibility of this framework. Since this research has found that one of the largest barriers to the wider implementation of vertical farms is the financial implication, it is therefore assumed by this research that the industry will not welcome another financial burden. The software used here is free of charge and open-source. Furthermore, this framework encourages transparent data sharing and flexibility to integrate future developmental needs within the framework.

Overall, this thesis aims to demonstrate how the understanding of all the individual parameters and expertise that influence the field of vertical farming must be brought together to achieve a successful integration of this alternative agricultural practice.

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> *During the length of this PhD, I had a big gain and I had a big loss: I gave birth to my beautiful baby daughter who made this world a million times more wonderful; and I lost my dear Abuelita (my beloved Grandma), who was a second mother to me. This PhD was a real roller coaster… but life is a roller coaster! We must do our best to enjoy the ride while it last. Let’s make our time on this Earth count! Let’s make it worthy of future generations.*

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Jasmine and Libia
Life & Spirit

Publications

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Nomenclature

ACH	Air Changes per Hour. Unit commonly used to represent ventilation rates.
BIA	Building Integrated Agriculture.
BICEF	Building Integrated Controlled Environment Farm.
BLD	Building. Acronym used by HTB2 in the module focused on the characteristics of the host building.
CEA	Controlled Environment Agriculture.
HDVG	High Density Vertical Growing.
HTB2	Heat Transfer in Buildings (version 2). This is the software used to assist the framework developed in this research.
LED	Light Emitting Diode is a semiconductor device use as an alternative source of lighting.
PF	Plant Factories.
PFALs	Plant Factories with Artificial Lighting.
PPALs	Plant Production System with Artificial Lighting.
PPU	Plant Production Unit.
RAS	Recirculating Aquaculture Systems.
SD	Standard Deviation (statistical analysis parameter).
SRV	Services. Acronym used for the HTB2 module focused on the characteristics of the services of the vertical farm.
UF	Urban Farms.
VF	Vertical Farming.
ZFarming	Zero-Acreage Farming.

Foreword

> *The realisation is that it is no longer sufficient to talk about a more sustainable food system; but rather there is a need for a radical transformation of the system so as to deliver sustainable and healthy food for all in the face of shrinking resources and a growing global population.*
>
> (Sanderson and Marsden, 2020)

A Welsh Food System Fit for
Future Generations.

A report by the Sustainable
Places Research Institute at
Cardiff University.

Commissioned by
WWF Cymru.

Chapter 1
Introduction

"Moving towards cities that behave like ecosystems rather than parasites"

(Despommier 2013)

1.1 Background

Agricultural practices are at a significant crossroads: continuous population growth (Roser and Ortiz-Ospina 2018; Wilmoth 2018), increasing evidence of food shortage (Orsini et al. 2013; FAO et al. 2017) and reduced land availability (Garg 2017) are just a few of the problems highlighting the need to improve existing agricultural methods. Moreover, recurrent emerging episodes of catastrophic natural phenomena occurring across the world, such as global warming (Rosenzweig et al. 2008), increased natural disasters (Banholzer et al. 2014; IFRC 2016) and depletion of natural resources (IFRC 2016) are pushing the bar even higher, in terms of the urgent need to find viable solutions to tackle food security (Benke and Tomkins 2017; Nicholson et al. 2021). The research community is under pressure to find solutions towards the above issues in tandem with the protection of the natural environment and the need to improve quality of life (FAO et al. 2017).

In parallel, urban development and architectural challenges are also outlined by the severity of the issues mentioned above, which in a similar manner are the result of the continuous expansion of cities due to population growth (Ahern et al. 2014). Therefore, it is imperative to find solutions to minimise the impact of urban development on the planet (Hasse & Lathrop 2003; Johnson 2001; Despommier 2009).

There is compelling evidence of the positive impact of the integration of green and agricultural elements into the built environment and how they help to mitigate some of the damage caused by extensive urbanisation (Alexandri and Jones 2008; Safikhani et al. 2014; Benis et al. 2017b; Al-Kodmany 2018; Bustami et al. 2018).

1.2 Research Aim and Objectives

The **aim** of this thesis is to explore the potential and required future development of a simulation-based modelling framework to meet the needs of vertical farming. The main target of this framework is to provide a replicable methodology that can be expanded to integrate further aspects of vertical farms. This is with the wider purpose of improving our understanding of the concept of vertical farms, bringing together the variety of theories that are attached to this industry. The investigation proposes an analytical and conceptual framework to test a quantitative approach (simulation) to advance the knowledge in the area of the design of vertical farms. The framework developed is assisted by an open-source software tool and encourages future multidisciplinary collaboration and data-sharing.

The main **objectives** to achieve this aim are:

1. To review the State-of-the-Art of vertical farming, the different methods used in this alternative agricultural practice and establish the most appropriate method(s) to be recreated through the simulation process and data analysis.
2. To propose, develop and test a conceptual and analytical framework that can be used to recreate or modify the behaviour of vertical farms in indoor environments, with the assistance of a flexible simulation tool.
3. To test the simulation framework developed, in order to assess an active vertical farm (case study). Including the assessment of the

framework to allows the prediction of important parameters relevant to establishing an optimum environment required for the building to host a vertical farm indoors.

The framework developed in this investigation can potentially be used as a standardised approach to assess vertical farms at an early design stage. By integrating this method potentially as a vertical farming platform, this field can perhaps be further developed in a collaborative manner, by encouraging community research engagement and transparent data-sharing in a multidisciplinary manner. Perhaps empowering researchers to develop benchmarks to share data across different countries, with the focus on optimisation of indoor environments for plant produce in buildings. These characteristics can act as a catalyst for more collaboration and therefore allowing larger multidisciplinary teams working together towards achieving greater efficiency and affordability of vertical farms.

1.3 Focus Context

Nature has inspired humans to find solutions to a number of problems (Lurie-Luke 2014), this is also known as *biomimicry* or *biomimetic* (Dash 2018; Kuru et al. 2019). There are several examples within architecture where the integration of plants provided the best solutions to specific problems (Pawlyn 2011; El-Zeiny 2012; Rao 2014; Bingham-Hall 2016).

Nature inspired solutions offer a significant source of knowledge-transfer opportunities, as other researchers have already demonstrated (El-Zeiny 2012; Breuste et al. 2013b). The synergy between plants and buildings can be seen within the world of *biomimicry* where it has been exploited to some extent in the built environment (Kuru et al. 2019), nevertheless, examples of it at a large scale are a lot scarcer. Therefore, it is interesting that one of the largest advocates of vertical farming, Prof Dickson Despommier describes our cities as “parasites” (Despommier 2013). He suggests that the concept of vertical farming, particularly integrated within cities, can hold the key to help our cities to behave as “ecosystems rather than parasites” (Despommier, 2013). This concept could potentially be described as urban-scale biomimicry, by aping the logic described above.

To elaborate on this point, a comparison of Despommier’s remarks have been included in Table 1 below. The various concepts have been extracted from Oxford specialist dictionaries (Table 1).

It can be noted that viewing these concepts from the perspective described above, i.e. cities compared to ecosystems or parasites, brings to the surface the similarities between these concepts and the behaviour of cities. Unfortunately, due to poor planning, lack of holistic design and disregard of the impact of urban development on the natural environment, cities have developed over the years in a way that resembles more the concept of “parasitism” rather than the concept of a sustainable “ecosystems”.

Cities can truly be compared to complex living organisms that often grow organically according to the needs of its inhabitants (Berg 2013), this is the biomimicry principle (Kuru et al. 2019). By replicating the behaviour of living organisms and learning from the principles of biology, cities mechanisms can be directed towards finding more efficient solutions (Pawlyn 2011). Interestingly, Garcia-Holguera et al (2015) attempted to develop a “transdisciplinary design approach rooted in the field of biomimetics [which] emulates the interrelated complexity of the parts of an ecosystem with the intent to design buildings that are more efficient, effective and holistic. Ecomimetics refers to the design of buildings that mimic ecosystem processes and functions” (Garcia-Holguera et al. 2015). In their investigation, Garcia-Holguera et al found that one significant challenge to the application of ecomimetics is the lack of systematic methods available or published. This can be strongly related to attempts made to apply any sort of ecomimetic (or biomimetics/biomimicry) in the wider urban context (Dash 2018; Kuru et al. 2019), i.e. to emulate the interrelated parts of an ecosystem to design more efficient and effective cities.

Table 1. Biology concepts compared to cities in terms of biomimicry

Ecosystems	***Parasites***
"A term first used by A. G. Tansley (1871–1955) in 1935 to describe a natural unit that consists of living and non-living parts, interacting to form a stable system. Fundamental concepts include the flow of energy via food chains and food webs, and the cycling of nutrients biogeochemically. Ecosystem principles can be applied at all scales" *- Oxford dictionary of zoology* *"A biological community and the physical environment associated with it. Nutrients pass between the different organisms in an ecosystem in definite pathways […]. Nutrients and energy move round ecosystems in loops or cycles"* *- Oxford dictionary of biology* *"A community of plants and animals within a particular physical environment that is linked by a flow of materials through the non-living (abiotic) as well as the living (biotic) sections of the system"* *- Oxford dictionary of geography*	*"A plant or animal that lives in or on a host (an animal or plant of a different species) for at least part of its life, from which it obtains nutrients or some other necessity."* *- Oxford dictionary of environment and conservation.* ***Parasitism*** *"An interaction of species populations in which one (typically small) organism (the parasite) lives in or on another (the host), from which it obtains food, shelter, or other requirements. […] Parasitism usually implies that some harm is done to the host"* *- Oxford dictionary of zoology* *"An association in which one organism (the parasite) lives on (ectoparasitism) or in (endoparasitism) the body of another (the host), from which it obtains its nutrients"* *- Oxford dictionary of biology*

Researchers have discussed the movement from the typical linear economy in cities and create a paradigm shift into a circular economy (Pawlyn, 2011; Berg, 2013), becoming creative with waste streams, for instance, and include waste into a useful process (i.e. anaerobic digestion, converting waste into energy). One example of this is the vertical plant in Chicago, The Plant (Kalantari et al. 2017b). Nate Berg (2013) published an article describing a number of concepts related to biomimicry and how cities can learn from nature. "From stronger building materials to more intuitive water systems, biomimicry has applications in urban infrastructure that can dramatically improve the way we live in cities (Berg 2013; Dash 2018; Kuru et al. 2019). Along the same line, Samangooe et al (2016) suggest that cultivating food on buildings could be the key to making every element of a city multifunctional and contribute to its sustainability and habitability. Here these concepts are illustrating how cities already have some of the tools to behave as 'ecosystems'. "The goal of green buildings is to use only as much energy and resources and create only as much waste as can be sustained by the environment" (Hanks 2009). All these authors have in common that they present a picture of an 'active' system of a city, which produce as much as it consumes, instead of 'sucking' and wasting resources from other sources. In this way cities can effectively behave as ecosystems, rather than parasites, as stated above.

However, all these concepts make for an interesting read, but are they truly possible? In order to achieve this level of large-scale development and improvement, which can potentially help to solve so many systematic problems, requires significant interventions: Disruptive innovation (Kivimaa et al. 2021). Within this context, this disruptive innovation most likely will require to take place in the areas of building design and food production symbiotically (Colnago et al. 2021). Perhaps technology holds the key to help cities move in this direction (Despommier 2010). However, sometimes technological advances are perceived to go against the natural environment (Enzi et al. 2017). Nevertheless, in terms of protecting and enhancing natural biodiversity in cities, technology has helped to push the boundaries of urban greening and agriculture. For example, "the development of green roof and wall technologies has always been firmly based in an ecological approach" (Enzi et al. 2017).

> "Vertical agriculture represents a synthesis of architecture, technology, gardens, and agriculture, aimed at taking form in the places of residence and every day urban life" (Torreggiani et al. 2012).

Urban agriculture (UA) has been practiced for a number of years (Kozai et al. 2016b; Kalantari et al. 2017b; Graamans et al. 2018; Shamshiri et al. 2018) and it has been highly dependent on available technology (Viljoen et al. 2005; Viljoen and Katrin Bohn 2014; Molin and Martin 2018a), especially when it is practiced under shortage of natural resources, such as: sunlight, soil, water, nutrients, etc. Dependency on this technology puts significant strain on the development of urban agricultural diversified practices, mainly indoors, due to the financial constraints (Kozai et al. 2016a). Land availability within cities is usually an expensive commodity, therefore urban growers have the need to maximise the space, as well as other resources (Viljoen et al. 2005; Kozai et al. 2016a). Similarly, the use of water in high-demand areas comes at a significant cost. Furthermore, the available sun-access is usually limited within the urban fabric, due to surrounding buildings and suitability of areas to grow. Even if the crops are growing outdoors, due to the typical morphology of cities, surrounding buildings will almost always cast shade at different times of the day. In order to tackle the issue around land availability within urban environments, some vertical farming ventures have been the result of repurposing unutilised urban spaces such as the Plant in Chicago, UF De Schilde in the Hague, Aero Farms in New York and Grönska in Stockholm (Molin and Martin 2018a).

Thorough studies and experiments in the area of urban greening and urban farming have taken place in a number of research projects around the world, including the concept of vertical farming (Alexandri and Jones 2008; Torreggiani et al. 2012; Koyama et al. 2013; Banerjee and Adenaeuer 2014a; Pérez et al. 2014). However, despite all the advances and research evaluating the integration of green elements and farming activities in cities, less sustainable agricultural practices are predominant (Breuste et al. 2013a; Kozai 2013b; Al-Chalabi 2015; Davis and Hirmer 2015; Higgins 2016), this highlights the need for more research in the area of alternative agriculture. A recent event highlighted in the international news was a reminder of the vulnerability of the world of imports and exports; the incident in the Suez Canal, where a large container ship blocked the canal for almost an entire week (BBC News 2021). This event was particularly impactful due to the strategic importance of the Suez canal which "is one of the busiest trade routes in the world with about 12% of total global trade moving through it" (BBC News 2021). This event represented significant financial implications and a negative impact on the supply of current demands, i.e. "£7bn of goods being held up each day" (BBC News 2021). This episode portrayed a severe lesson to remind countries about the importance of diversification and planning for alternative resources, as well as to strive to become more self-reliant. Agriculture represents a significant portion of imported goods in the UK (Prakash 2018; Cadillo-Benalcazar et al. 2020) and therefore the country is in a vulnerable position by being highly dependent on international food production. The evolution and improvement of technological developments can "play a key role in determining the future competitiveness of the UK food and beverages sector. […] policy makers may nurture innovation by supporting research [into] healthier, tastier and convenient food" (Prakash 2018).

In addition to all the significant issues mentioned above, related to food security, air pollution, water preservation, etc., there is also an important driver to continue research in the area of urban plants and food production: The preservation of plant species themselves and biodiversity (Harkness et al. 2021). This is interestingly expressed by Lewis-Jones (2016) where he explores the common marginalisation of plants throughout the development of the human race. In this publication, a reflection is made regarding how plants have been relegated to "a green background to human activity" (Lewis-Jones 2016; Rival 2016; Sheridan 2016). However, the authors emphasised that recent research is helping human knowledge to better understand the role of plants in human development. Nevertheless, the increase in urbanisation and reduced direct contact with plants is leading the general public towards "*plant blindness*- an inability to visually and conceptually distinguish and interpret a botanical world that has been strip of meaning" (Wandersee and Schussler 2001; Lewis-Jones 2016). In turn, this has led to the decrease of biocultural diversity, and the drastic changes of land use has increased the number of plants threaten with extinction (Lewis-Jones 2016; RBG Kew 2016):

> *"As we lose plant species to extinction we nor only lose their evolutionary heritage, adaptations, ecosystems functions, and their potential uses, but also diminish the inherent resilience and intrinsic value that biodiversity brings"* (Smith et al. 2011; Vucetich et al. 2015; Lewis-Jones 2016)

The increase in urban farming activities can potentially improve the knowledge of plants of the general public, making this a compelling case for encouraging growth of urban vertical farming practices, since they can either be implemented in cities as well as rural areas, as mentioned earlier in this chapter. Correspondingly, there is significant evidence highlighting the need to develop further research in the area of architectural sustainability with the integration of plants (Breuste et al. 2013a; Yang et al. 2015; Centre for Sustainable Energy 2015).

Therefore, the main focus of this PhD investigation is primarily on vertical farms, with reference to related alternative urban agricultural and green elements. The key novel contribution of this research is particularly centred on the development of a simulation framework methodology for vertical farms.

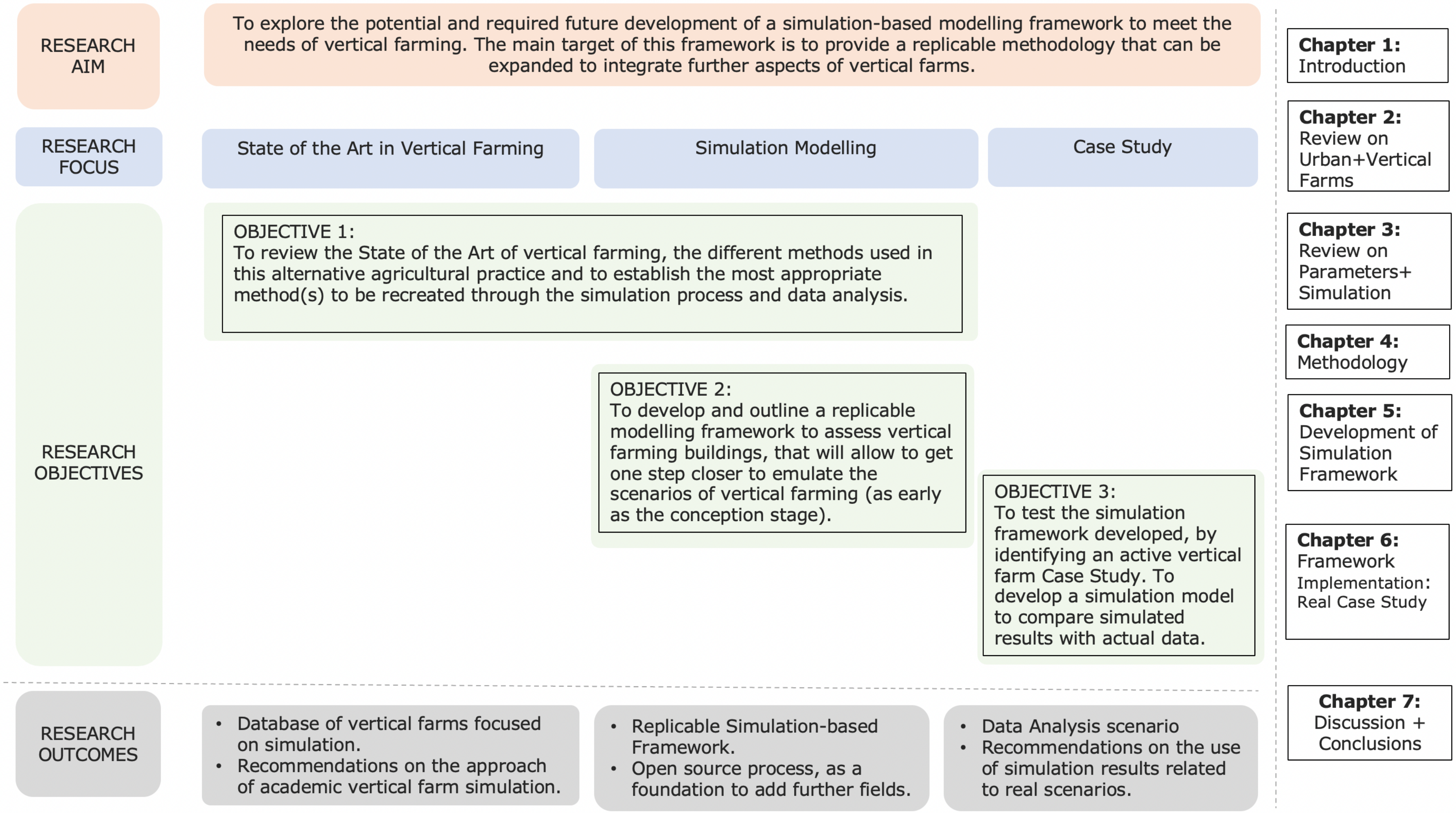
This PhD is part of the ***Plants and Architecture*** Workpackage for the Sêr Cymru National Research Network for Low Carbon Energy and Environment (NRN-LCEE 2018).

1.4 Thesis Overview

This section presents an overview on the structure of the thesis and the novel contribution to knowledge. Figure 1, presents the relationship between the research aim, objectives, outcomes, and each of the chapters of this thesis.

1.5 Structure of the Thesis

This thesis comprises 7 chapters, these are outlined in the schematic below (Figure 1):



RESEARCH AIM

To explore the potential and required future development of a simulation-based modelling framework to meet the needs of vertical farming. The main target of this framework is to provide a replicable methodology that can be expanded to integrate further aspects of vertical farms.

RESEARCH FOCUS

State of the Art in Vertical Farming

Simulation Modelling

Case Study

RESEARCH OBJECTIVES

OBJECTIVE 1:
To review the State of the Art of vertical farming, the different methods used in this alternative agricultural practice and to establish the most appropriate method(s) to be recreated through the simulation process and data analysis.

OBJECTIVE 2:
To develop and outline a replicable modelling framework to assess vertical farming buildings, that will allow to get one step closer to emulate the scenarios of vertical farming (as early as the conception stage).

OBJECTIVE 3:
To test the simulation framework developed, by identifying an active vertical farm Case Study. To develop a simulation model to compare simulated results with actual data.

RESEARCH OUTCOMES

- Database of vertical farms focused on simulation.
- Recommendations on the approach of academic vertical farm simulation.

- Replicable Simulation-based Framework.
- Open source process, as a foundation to add further fields.

- Data Analysis scenario
- Recommendations on the use of simulation results related to real scenarios.

Chapter 1: Introduction

Chapter 2: Review on Urban+Vertical Farms

Chapter 3: Review on Parameters+ Simulation

Chapter 4: Methodology

Chapter 5: Development of Simulation Framework

Chapter 6: Framework Implementation: Real Case Study

Chapter 7: Discussion + Conclusions

Figure 1. Structure of the thesis and the relationship between aim, objectives, outcomes, and the thesis chapters

1.6 Novel contribution to knowledge

The outcomes of this research contribute to improve the current methods to assess vertical farming buildings. By having a standardised framework, different vertical farms across the world can be compared and new efficiency benchmarks can be developed, encouraging multidisciplinary collaboration and transparent data-sharing.

This investigation aimed to deliver a step change in:

I. The development of a novel analytical and conceptual framework, supported by simulation (based on HTB2), to appraise the viability of vertical farming buildings at an early-stage of the design process. The area of simulation of vertical farms have very little development and there are no open-source, freely available tools to undertake this analysis. This is one of the main gaps this investigation tackled.
II. This framework has the potential to allow future vertical farms design to be optimised before they are built. This results in the tacit contribution to better and more energy-efficient vertical farms being deployed in the future, by using this framework to forecast different scenarios of energy consumption with the potential to assess renewable energy integration, where possible.

Chapter 2
A Review on Urban and Vertical Farms

*"I can do things you cannot, you can do things I cannot;
together we can do great things."*

(Mother Teresa)

2.1 Chapter Overview

This chapter provides a detailed recount on the background and development of vertical farms. It starts with a depiction of the historic development of Vertical Farming, accounting for the different methods used across different periods of time. Subsequently, a timeline of events presents the development of the term "Vertical Farm" from the viewpoint of several disciplines. Also the systematic literature review method is described in this chapter.

2.2 Introduction

The initial focus of this research started from the premise that the TWO selected fields, shown in Figure 2, possess the potential to have a significant positive contribution towards the mitigation of the problems mentioned in Chapter 1 when combined in research and development. The TWO key areas being the basis of this investigation are:

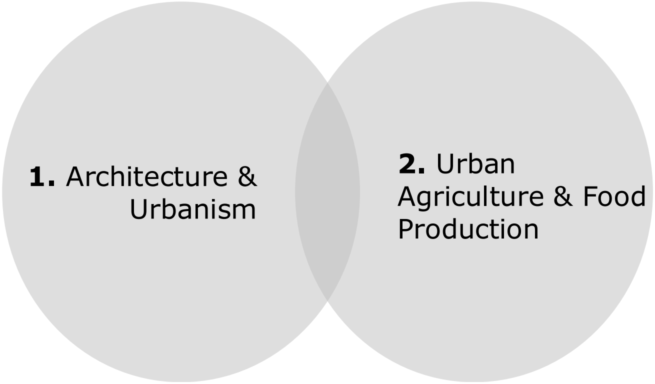


Figure 2. Investigation Focus, Initial boundary fields.

1. **Architecture and Urbanism Focus:** Provide the potential to improve buildings and neighbourhoods with a holistic approach, which can be founded on sustainable design (Gillott et al. 2010; Ahern et al. 2014; Torcellini et al. 2015). Biodiversity should always be encouraged throughout this practice, by implementing environmentally inclusive and adaptive architecture and urbanism (Lu and Qu 2018; Fallmann and Emeis 2020; Zune et al. 2020).
2. **Urban Agriculture and Food Production Focus:** Current methods to produce, store and distribute food are in urgent need of optimisation (Gras and Cáceres 2020; Liebe et al. 2020). Agriculture ought to impose significantly less damage to the natural environment (RockstrÖm 2009; Englund et al. 2020). Alternative methods of agriculture and diversification of production will contribute towards enhancing food production in general and mitigate food poverty (Doane 1944; Viljoen et al. 2005; Orsini et al. 2013).

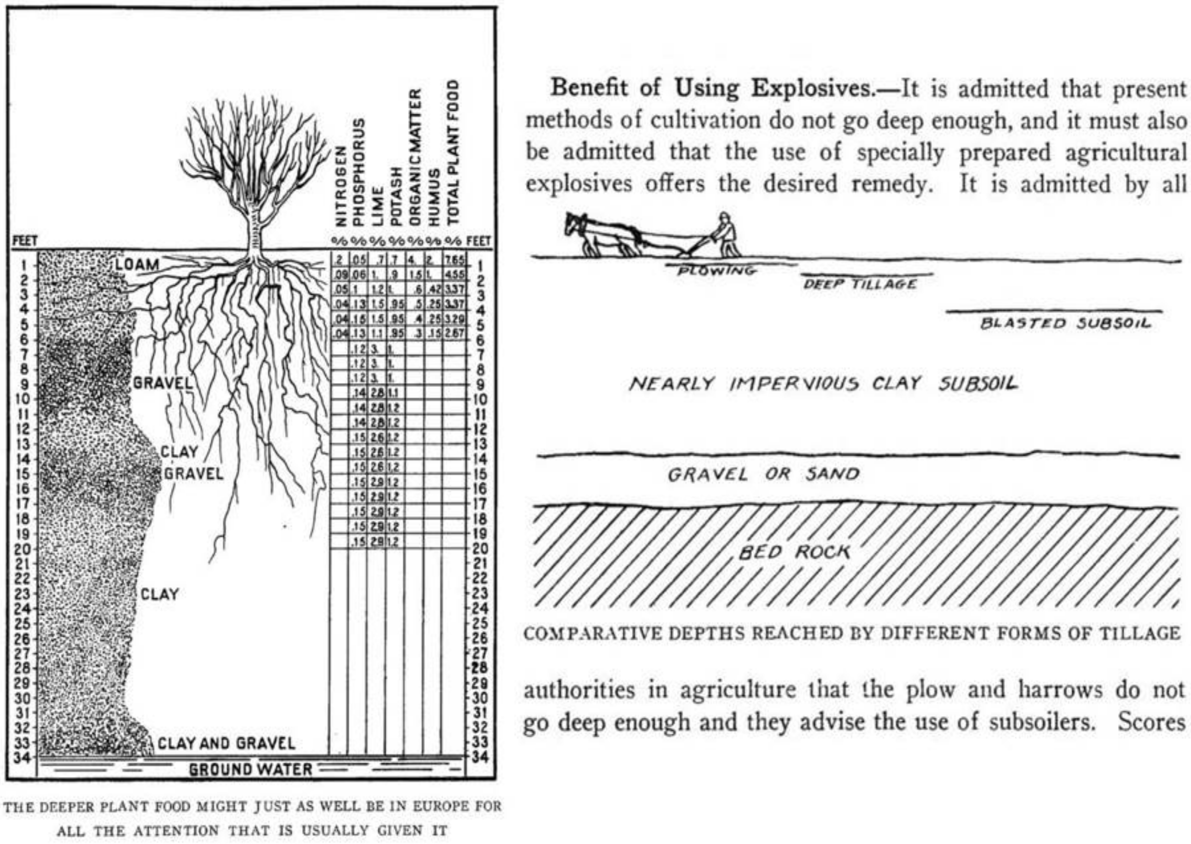
Henceforth, this research departs from establishing a common focus within the two key overlapping areas aforementioned. The beginning of this research aimed to gather scientific evidence to evaluate current advances of the integration of agricultural and green elements within buildings and cities in general, taking under consideration viability, sustainability and levels of research undertaken in these areas.

During the initial literature review, it was found that there is an urgent need to make cities more sustainable and in general greener (Howard 1965; Viljoen et al. 2005; Lim and Liu 2010; Viljoen and Katrin Bohn 2014). Although sustainability principles are increasingly used to guide neighbourhood development (Gillott et al. 2010; Cohen and Naginski 2014; Sharifi 2016; Coma Bassas et al. 2020), urban sprawl is creating a number of negative issues in cities, such as air and water pollution, increased noise levels, reduced vegetation, increased UHI Effect (Urban Heat Island) and global warming (Alexandri and Jones 2008; Li et al. 2011; Safikhani et al. 2014; Molin and Martin 2018a).

Nevertheless, cities also have characteristics that can hold the key to find solutions to some of these problems, this has been eloquently described by Lim and Liu (2010) using the label of "Cities as solutions". In their book they describe how high-density mixed-use cities can be made more sustainable by implementing better planning strategies, which consider the integration of various key factors such as maximising land-use by developing tactical vertical and horizontal zoning. This would also allow and encourage urban agriculture and energy generation at a meaningful scale, as well utilise, repurpose and share waste products for improved productivity (Lim and Liu 2019). The above somehow echoes Despommier (2013) remarks, when he suggests that further research and development in the area of buildings and agriculture must take place to help our cities achieve their potential to behave as ecosystems rather than parasites, which was also touched upon in Chapter 1. As a result, this research explored different topics related to potential areas that could belong to the overlapped section shown in Figure 2. Vertical Farms was one of these areas, it was amongst other potential topics that were considered at the early stages of this investigation, the sections below will reveal the reasons identified to f along the way and the sections below will describe the various and different reasons of how Vertical Farming became the main topic of this investigation.

2.3 Historic Development of Vertical Farming

Historically, the term 'Vertical Farming' originated back in 1915, it was used in a publication by Prof Gilbert Ellis Bailey, a Professor of Geology at the University of South California (Bailey 1915). In his book he coined this term also using it as the title of his book: *Vertical Farming*, he described it as a soil-based type of agricultural development (Figure 3). In his book, Professor Bailey explores a number of issues, mainly related to several of the characteristics and properties of agricultural soil, such as soil texture, chemistry, soils moisture, etc. He concluded his book by establishing that with the use of inexpensive explosives, farmers can effectively farm deeper into the soil layers. Thus, increasing the acreage available in their fields and therefore obtaining larger crops (Bailey 1915). Despite the fact that this book does not use the term vertical farming as it might be perceived nowadays (Despommier 2010; Sarkar and Majumder 2015), with his



THE DEEPER PLANT FOOD MIGHT JUST AS WELL BE IN EUROPE FOR ALL THE ATTENTION THAT IS USUALLY GIVEN IT

Benefit of Using Explosives.—It is admitted that present methods of cultivation do not go deep enough, and it must also be admitted that the use of specially prepared agricultural explosives offers the desired remedy. It is admitted by all

COMPARATIVE DEPTHS REACHED BY DIFFERENT FORMS OF TILLAGE

authorities in agriculture that the plow and harrows do not go deep enough and they advise the use of subsoilers. Scores

Figure 3. Diagrams and passage from the first book
entitled Vertical Farming, pp 25 & 63
Source: Bailey (1915)

notions, Professor Bailey created an initial foundation of a concept that will thereafter be shared with the modern understanding of vertical farms: “Instead of spreading out over more land [the farmer] concentrates on less land and becomes an intensive rather than extensive agriculturist” (Bailey 1915).

In this first book, the author talks about intensive agriculture in a reduced area of land, in terms of deeper levels into the ground. The modern concept of vertical farming aims to achieve a similar outcome, but instead of using explosives to reach deeper layers of soil, modern vertical farms commonly use the vertical stacking of layers of crops (Figure 4), or utilise various storeys of a building (Despommier 2009; Banerjee and Adenaeuer 2014b) to achieve this concept of “intensive rather than extensive” agriculture. Modern vertical farms can achieve this by using a number of different techniques, such as Recirculating Aquaculture Systems (RAS), i.e. aquaponics, as well as hydroponics, aeroponics, or soil-based vertical systems. (Fischetti 2008; Besthorn 2013; Hughes 2018; Khandaker and Kotzen 2018; Molin and Martin 2018a). Furthermore, modern vertical farms are not required to be underground (although they can be, as

Figure 4. Pictures taken by the author during a site visit to

described by Ward R et al. (2018) and Jans-Singh et al. (2019)), vertical farming is a type of alternative farming that can take place above ground, as well as indoors or outdoors. Due to this versatility of vertical farms, this concept could provide solution for extreme situations such as growing food in space, poles and refugee camps (Banerjee and Adenaeuer 2014b).

Currently, some of the most profitable and common crops are: green leafy vegetables, cabbage, lettuce, basil, tomatoes, okra, cantaloupe, bell peppers and roses (Sarkar and Majumder 2015). The latest research analysing various types of cultivation of edible plants on buildings also shed some light in terms of the benefits and limitations of soil-less and soil-based agriculture (Samangooei et al, 2016). Their investigation assessed a number of case studies under a scoring system using these parameters: Environmental, Social and Economic impact. Such study revealed that soil-less systems (such as hydroponic vertical farms) are more productive per square meter. However, soil-based systems are more affordable and are more likely to be more environmentally and socially beneficial overall. Nevertheless, (Samangooei et al. 2016) admit to be only at the beginning of a larger exploration of the two types of cultivation systems (i.e. soil-less and soil-based). They conclude their research article with the following remark: "Cultivating food on buildings and how we can do this is key to making every element of a city multi-functional and contribute to its sustainability and habitability" (Samangooei et al. 2016).

Briefly explained, ***Hydroponics*** is the predominant method used in vertical farming (Gupta and Ganapuram 2019) to grow plants by using a water based solution system rich in nutrients, without the use of soil or other solid growing medium (Holland Hydroponics & Horticulture 2016; Waldron 2017; Hughes 2018; Gupta and Ganapuram 2019), as can be seen in Figure 5 below.

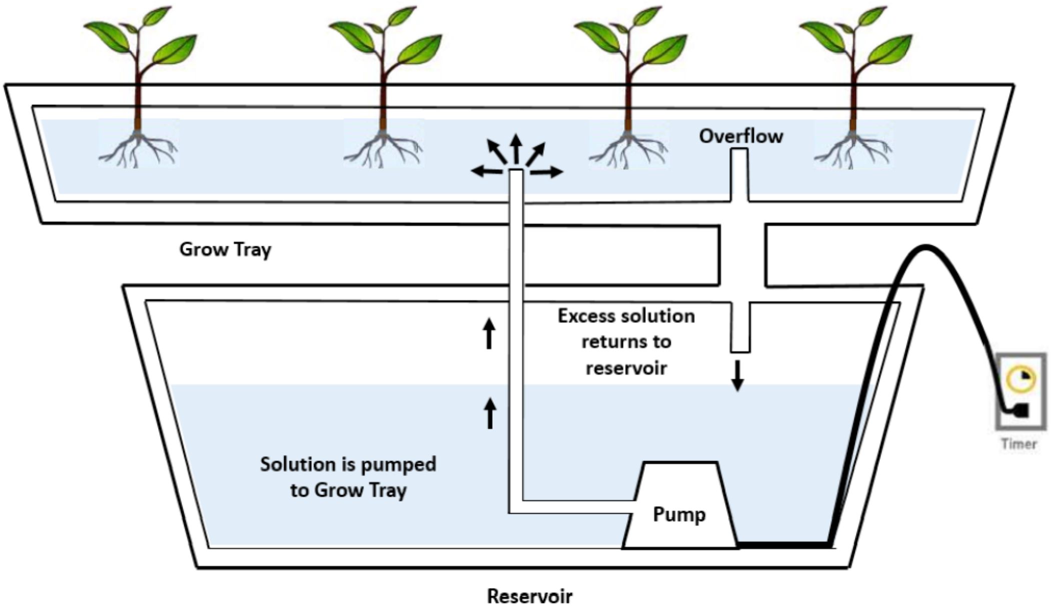


Figure 5. Schematic diagram of a hydroponic system.
Source: Gupta and Ganapuram (2019)

Similar to hydroponics described above, ***Aeroponics*** is also a soil-less method of growing plants, but instead of submerging the roots of the plants in a water-based solution, the roots are suspended in air, allowing a greater exposure to oxygen for improved nutrients-absorption, see Figure 6. The roots are nourished by using small microjets or water-mist which spray the roots with a nutrient rich solutions at regular intervals (pH Hydro 2014; Hughes 2018; Gupta and Ganapuram 2019).

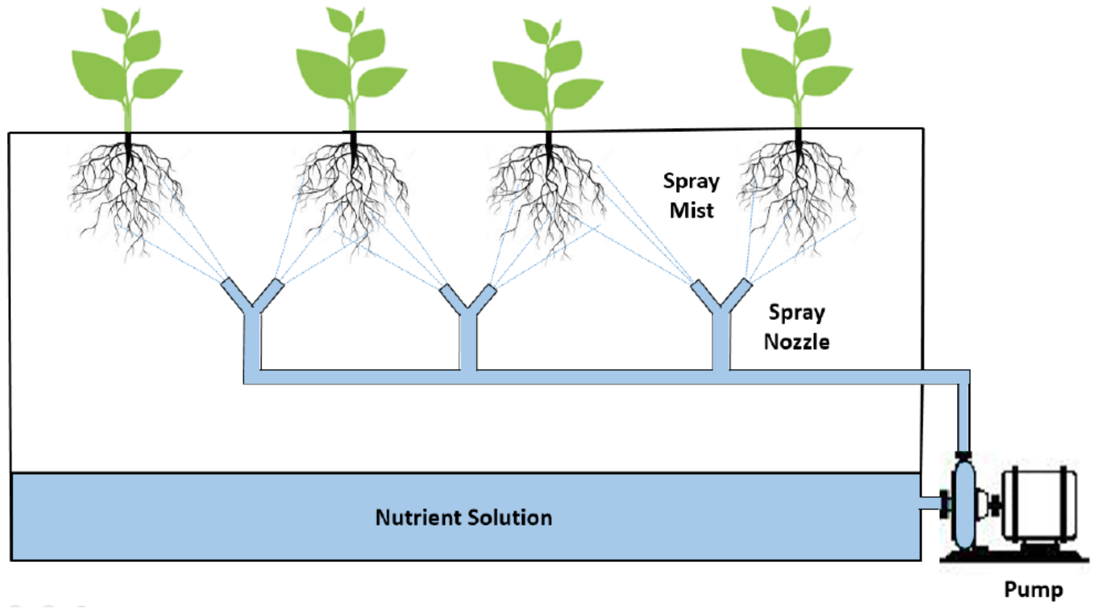


Figure 6. Schematic diagram of an aeroponic system.
Source: Gupta and Ganapuram (2019)

Aquaponics is similar to hydroponics (previously depicted in Figure 5), but instead of using nutrient-solutions to enrich the water based growing medium, fish waste is used to provide an organic food source for the plants, with the added value that plants also help to filter the water for the fish to thrive (The Aquaponic Source 2016; Waldron 2017; Gupta and Ganapuram 2019). In technical terms, aquaponics is an integration of Recirculating Aquaculture Systems, also known as RAS (Somerville et al. 2014; Khandaker and Kotzen 2018), which means it combines aquaculture (raising fish) and hydroponics to grows fish and plants together in one integrated system (The Aquaponic Source 2016; Gupta and Ganapuram 2019). Figure 7 provides an example of aquaponics, nevertheless the growing medium for the plants can be soil-based (as shown in Figure 7) or it can be water-based (similar to the grow tray of the scenario depicted in Figure 5, in the example of a hydroponic system).

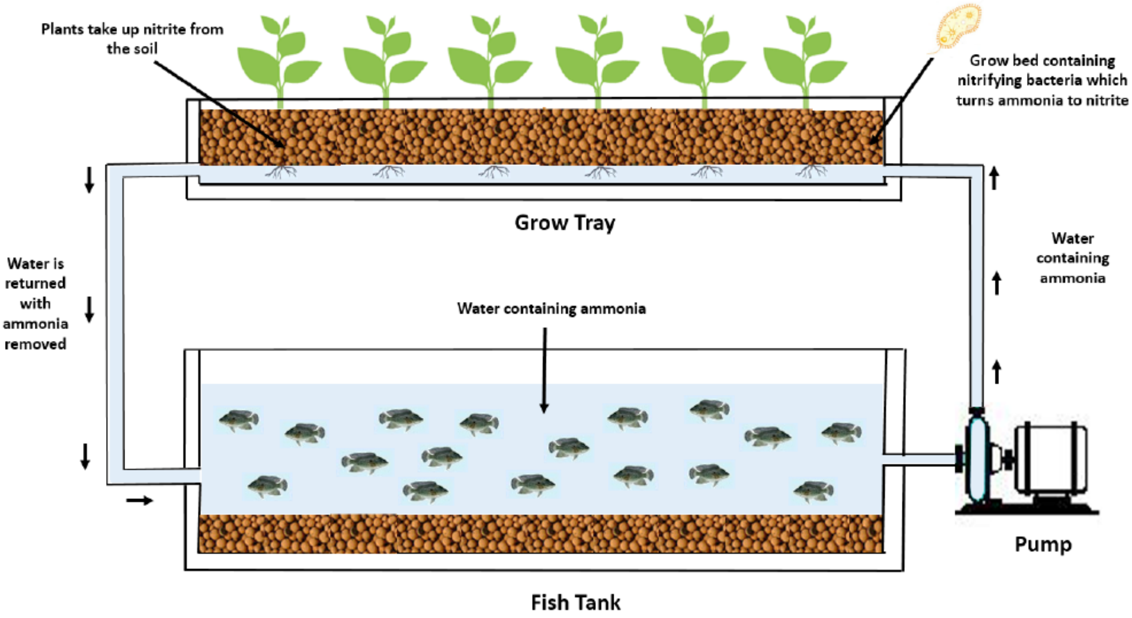


Figure 7. Schematic diagram of an aquaponic system.
Source: Gupta and Ganapuram (2019)

The above information is a sample of the main types of current vertical farms, but there are various other types of arrangements that can be found in modernity. These diagrams provide a visual that emphasise the significant difference of current vertical farms compared to the ones described in 1915 (Bailey 1915). The field of vertical farming has evolved throughout the years and there have been a number of different events that have influenced its evolution. Due to the multidisciplinary nature of this field (Despommier 2010; Kozai et al. 2016a; Benis and Ferrão 2018; Kozai 2018; Ryymin et al. 2020) various sources from different disciplines have been gathered to develop a timeline tailored to the context of this thesis.

2.3.1 Timeline Development of Vertical Farms

The main focus of this historic review has evolved around the development of the term "vertical farming", as well as further relevant events in history directly related to the systems and methods that have been used to implement and develop different versions of vertical farms. The inclusion of historic references also considered some of the most significant architectural developments in the area of building integrated agriculture and plant growing, attempting to remain within the remit of vertical farming. Building integrated agriculture and plants can overlap significantly with the area of green walls/roofs, but to maintain a manageable scope for this investigation, only the areas that are specifically related to vertical farming have been included in this timeline. On a similar note, there is a related concept known as *Plant Factories*, which is the term used in some countries as an equivalent name for vertical farms. Nevertheless, the author of this thesis does not consider the two terms as synonyms albeit related. This is further discussed and explained later in this chapter. However, for this historical recount of events that contributed to shaping the development of vertical farms, the term Plant Factories is highly relevant (as well as other concepts that are closely related to vertical farms), hence it has been included.

There have been a series of relevant events from a number of different disciplines that have occurred simultaneously; therefore, in order to help the reader to identify key aspects related to different disciplines, the following colour-coding system was used:

Vertical Farm terminology

This colour represents any of the historic events related to the term "Vertical Farm" or its variations.

Hydroponics

Events marked in blue are related to developments in the field of hydroponics or similar.

Agriculture integrated in Architecture

Events marked in green are related to developments in the area of the integration of agriculture or some greenery within buildings.

Health and Wellbeing

Events marked in purple are related to research in the area of health and wellbeing.

Plant Factories

Events marked in orange are related to the development of plant factories systems/technology (this term will be described later in this chapter).

Lighting

Events marked in brown are related to the evolution of lighting technology for the purpose of indoor agriculture.

Following the above conventions, find below the timeline describing the main events identified through this literature review. These events have been considered to have a significant impact through history to help shaping the concept and practice of Vertical Farming:

1627

First published theory of a novel method of gardening without soil, by using only water (Bacon et al. 1627), this concept is now known as "hydroponics". Nevertheless, the term "hydroponics" was coined much later in history (see below). However, this method had already been used by the Aztecs to grow their crops on floating marshes on the lake in 1150 AD (Piccolino 2013). Nevertheless, Sir Francis Bacon (scientist and philosopher) first introduced this farming method in his publication of a series of experiments of natural history (Bacon et al. 1627; Piccolino 2013).

1699

John Woodward (scientist) published experimental work investigating if plants used the nutrients from water or soil to thrive (Asao 2012). Using water culture experiments, he found that plants thrived better in less pure water, since they derive minerals from soil mixed into water (Piccolino 2013).

1859

From 1859 till 1965 Julius Von Sachs and Wilhelm Knop experimented with the first attempts to add nutrient to water culture. They suggested a standard technique of research called "solution culture", which is currently widely used in hydroponics (Asao 2012).

1909

Satirical Life Magazine published a "realistic-looking diagram" of what is considered to be the earliest illustration closely related to the concept of vertical farms (Piccolino 2013; Martínez Muñoz 2020). The drawing depicted an 84-level steel frame of vertically stacked homes, each level containing a piece of garden city, even allowing for the development of agriculture (Piccolino 2013; Martínez Muñoz 2020). This drawing was significantly ahead of its time and it is known as "the Theorem of 1909" (Martínez Muñoz 2020). The principles of this Theorem have been revisited by a number of architects throughout history (see below: Habraken, 1962; Koolhas, 1978 and SITE 1972). Nowadays, there are several building projects that have demonstrated proof of concept (see below: Cosmo Park, 2009 and other below).

1915

The book titled: "Vertical Farming" is published by Professor Gilbert Ellis Bailey (geologist). This is where the term "vertical farming" was originated (further details of this publication have been discussed above in this chapter).

1922

Designs of the Architect LeCobusier are some of the earliest attempts to tackle high-density urbanisation, whilst considering the importance of integrating nature in buildings. In 1922 LeCobusier designed Immeuble-Villas (Boesiger and Stonorov 1937) that aimed to be a five-storey apartment block which allowed the integration of green spaces for each apartment (Piccolino 2013). Although the complete project was never built (only a test prototype unit) (Malott et al. 2015), this concept of integration of green spaces within buildings continued during the professional life of LeCobusier. Other relevant designs of his that can be directly related to vertical farming is the Cité-jardin vertical, 1935 (vertical garden city). This was a conceptual design project (not built), he envisaged for Algiers and Barcelona and it was shared during a lecture he delivered in Chicago in 1935" (Antonelli 2002; MoMA 2018).

1929

From 1929 onwards William Frederick Gericke (plant nutritionist) began his work in the commercial aspects of crop production via nutrition solution (Asao 2012; Despommier 2014).

1937

In 1937, William Frederick Gericke coined the term "hydroponics" (Piccolino 2013). "Hydroponic or soilless techniques have been used in many aspects of plant biology researches such as plant nutrition, heavy metals toxicity, identification of elements deficiency, screening for abiotic stresses, screening for aluminium toxicity, root functions and root anatomy" (Asao 2012).

1940

In the 1940s, experiments using artificial lighting for photobiology purposes took place (growing plants). Testing fluorescent lamps as a more efficient alternative to incandescent lights. It was discovered that fluorescent lamps "contain more than 10% blue wavelength of the total photon emission within the photosynthetically active radiation spectrum" (Mitchell and Sheibani 2015). Furthermore, hydroponic systems were used in the Pacific during World War II, where US troops cultivated fresh lettuce and tomatoes on barren islands (Piccolino 2013).

1944

In 1944, a paper was published titled "Vertical Farm Diversification" (Doane 1944; Goodsell 1951). In this publication, the term vertical farm is used to describe a type of business model for regular agriculture, rather than referring to the concept of the alternative agricultural method, which is the subject matter of this thesis. Nevertheless, the concept Doane (1944) describes in this publication is still equally valuable to modern agriculture, and therefore worth highlighting in this review: "vertical diversification […] refers to the production of the most profitable crop, and then diversifying by doing other things with the same crop" (Doane 1944).

1949

"the Earhart Plant Research Laboratory at the California Institute of Technology in Pasadena developed the first greenhouse with control of lighting, temperature, humidity, CO2, wind, rain, and mist [also known as] pytotrons"(Hirama 2015).

1950

The 1950s witness the rise of several phytotrons in Japan. They "were installed in universities, biological, and agricultural research institutes." (Hirama 2015).

1957

"the agricultural faculty at the University of Tokyo installed a biological environmental control facility (biotron) that was able to control temperature, humidity, and artificial lighting. It was not only a phytotoron, but also an animal and insect environmental control laboratory for biological research purposes." (Hirama 2015)

1962

The term "supporting structure" term was coined by Habraken in his book Des dragers en de mensen, perhaps inspired by LeCobusiers work in 1931, "A", Fort l'Empereur in Algiers (Martínez Muñoz 2020). Also, it is claimed that Habraken's work was a "critique of the repetitive, massive, homogeneous constructions built in the postwar era to alleviate this shortage" (Nagore Setién 2011). Therefore, this work aimed to provide more flexibility to mass-housing, by giving the option to occupants to have a say on the design of their homes, for example, to integrate green areas within their apartments.

1970

During the 70s and 80s, Architect Jean Renaudie designed a series of building and urban planning projects integrating greenery and suitable small-scale agricultural spaces for residences at any level of a building. Some examples of his extensive portfolio of urban projects are: Danielle-Casanova, 1972; Jeanne Hachette, 1975; Town Center of Givors, 1980 and Villetaneuse, 1985. (Zoetmulder 2014).

1970

In parallel to the architectural developments described above, in Japan, the development of technology for indoor farming continued. During the early 70s, "Hitachi Ltd (as part of the Japanese Society of Agricultural, Biological and Environmental Engineers and Scientists), Takatsuji Masaki, was the first in the world to begin test runs with plant factory technologies." (Hirama 2015).

1970

In the late 70s experiments begin with Sodium Lamps as alternatives to fluorescent lamps. "High-intensity-discharge (high-pressure sodium and metal halide) lamps made it possible for a fixed spectral-output source of light to grow plants productively" (Mitchell and Sheibani 2015).

1975

"Allan Cooperman introduced the nutrient film technique in which a thin film of nutrient solution flows through plastic channels, which contain the plant roots" (Jones 2013; Piccolino 2013).

1978

This year was the revival of the concept of the "Theorem of 1902" from Life Magazine in the publication "Delirious New York", 1978, which was a work of the architect Rem Koolhaas (Koolhaas 2004; Martínez Muñoz 2020). Koolhaas work seem to merge the concept of the "Theorem of 1902" with the idea of the "supporting structure", by Habraken in 1962 (Martínez Muñoz 2020).

1979

Started the development of an interdisciplinary research area, which also relates directly to the added benefits of integrating vertical farms and plants within the built environment. In 1979, Professor Ulrich published some of his earliest work related to building occupants' health and wellbeing. Ulrich (an interdisciplinary researcher in architecture and medicine) began investigating "links between psychological wellbeing and physiological responses when individuals are exposed to nature" (Soderlund and Newman 2015) in the built environment. His work is further developed by other researches (see below) and it eventually becomes the foundation of "Biophilic architecture" (Soderlund and Newman 2015).

1979

"In the late 1970s, high-intensity-discharge (high-pressure sodium and metal halide) lamps made it possible for a fixed spectral-output source of light to grow plants productively. The first large-scale commercial indoor farm in the USA was Phytofarms of America, which used high-intensity discharge (HID) lighting of hydroponic vegetables and herbs" (Mitchell and Sheibani 2015).

1980

The 1980s witnessed a significant development in the area of indoor agriculture simultaneously in several countries: "America, large scale automated plant factories using natural sunlight became widespread. At the same time, in the Netherlands, plant production factories using artificial light as a supplement to grow flowers, ornamental plants, and seedlings also became prominent. In Japan, SPA (Speaking Plant Approach) biometric cultivation technologies were proposed by Hashimoto Yasushi" (Hirama 2015).

1981

Architect and Artist, James Wines proposed the concept "Highrise of Homes" (MoMA 2002; Piccolino 2013; SITE 2015). Wines described the Highrise of Homes project as a "vertical community" to "accommodate people's conflicting desires to enjoy the cultural advantages of an urban centre, without sacrificing the private home identity and garden space associated with suburbia" (MoMA 2002). The images of this project suggest a multi-storey residential building highly relatable to the “Theorem of 1902” and the “supporting structure” term suggested by Habraken, and it calls for a conventional steel tower framework (Piccolino 2013). “This housing structure offers apartment dwellers the unique advantages of garden space and personalized architectural identity in a multi-story condominium. The building is a steel and concrete matrix supporting a vertical community” (SITE 2015). Martinez Muñoz (2020) describes SITE’s work as the next step, taking inspiration from the concepts proposed by Koolhaas in 1978. Potentially also building on LeCobusier’s earlier architectural work of Immuebles-Villas in 1922. James Wines funded SITE: Sculpture in the Environment Architectural Group, in 1970 (MoMA 2002).

1989

“Architect Kenneth Yeang envisioned mixed-use buildings that move seamlessly with green space in which plant life can be cultivated within open air, known as vegetated architecture. This approach to vertical farming is based on personal and community use rather than production and distribution matters (Piccolino 2013; Agritecture 2014). Yeang designed the concept of “Bioclimatic skyscraper” (Couzens 2012)

1990

In Japan, significant work is undergoing to improve efficiency of indoor farming. With this focus “new techniques such as, fluorescent lighting based multiple-shelve cultivation systems, effective use of area for denser plant layouts, and cultivation panels floating on a flood bed have been developed” (Hirama 2015).

Simultaneously, in the US the 90s were also a significant time for the development of technology for indoor farming. Nasa was developing LED lights, searching for more efficient methods to grow plants with artificial lights (Mitchell and Sheibani 2015). Despite the fact that the first LED was initially patented in 1961, the first high-power (1-W) LEDs were only developed in the late 1990s. (Bourget 2008)

1999

Professor Dickson Despommier (Ecologist) published the book titled "The Vertical Farm Feeding the World in the 21st Century" (Despommier 1999). In this book, Despommier mainly promotes "mass cultivation of plants and animal life for commercial purposes in skyscrapers" (Piccolino 2013). He proposed a modern concept of vertical farms "several floors tall" (Despommier 2013; Piccolino 2013; Agritecture 2014). The graphical representation proposed by Despommier's vertical farms, are not dissimilar to the "Biophilic skyscraper" proposed by Yeang (see 1989 above).

2005

Building up from the work undertaken by Ulrich in 1979, a fellow researcher, Kaplan, followed his footsteps with his investigative work beginning back in 1989 (Soderlund and Newman 2015). These two researchers provided the initial foundations of what later became known as "Biophilic Architecture" (see also 1989). These researchers focused on occupants' health and wellbeing, impacted by natural elements in the built environment. "Both Kaplans' and Ulrich's theories have been put to the test in the years since they were first proposed, either directly or by studies revealing supporting results" (Soderlund and Newman 2015). In 2005, research undertaken by Berto (2005) "concluded that restorative environments and experiences that involve nature do greatly support mental fatigue recovery" (Berto 2005). This study along with others confirmed the theories initially posed by Ulrich and Kaplan, on the positive impact of integrating green elements within the built environment on the health and wellbeing of occupants (Soderlund and Newman 2015).

2006

A consortium event took place in the US: a conference gathered participants from academia, industry, government, finance, and civil areas "to further discuss The Biophilia Hypothesis. The focus was on practical implementation of the benefits of biophilia into urban design and architecture. From this conference emerged the book Biophilic Design: The Theory, Science, and Practice of Bringing Buildings to Life, which established cross-disciplinary foundations for a biophilic design approach to the built environment." (Soderlund and Newman 2015).

2006

"Nuvege, the forerunner in technology for the innovative growth method of hydroponically grown vegetables, developed their proprietary lighting network, which increases the return rate of vegetable growth by balancing light emissions that also advance photosynthesis through amplified levels of carbon dioxide" (Piccolino 2013; Agritecture 2014).

2008

"Hershey (2008) said that growing plants in solution culture is often easier than soil culture because there is no need for dirty soil, there are no soil-borne diseases or pests, irrigation is less frequent in solution culture than in soil culture, solution culture irrigation can be easily automated, roots are visible, and the root zone environment is easily monitored and controlled." (Asao 2012)

2008

"A Japanese national policy known as the "Economic Growth Strategy for Widespread Plant Factory Use" was launched to promote the spread of completely controlled environmental and solar based plant factory businesses." (Hirama 2015)

2009

"SkyGreen Farms built a vertical farm consisting of over 100 nine-meter tall towers in Singapore where green vegetables […] are grown, stacked in greenhouses, and sold at local supermarkets" (Piccolino 2013). Singapore's is the world's first hydroponics vertical farm, growing tropical vegetables by using minimal resources, i.e. water, land and energy. (Piccolino 2013; Agritecture 2014; SkyGreens 2014). "This farm “uses sunlight as its energy source, and captured rainwater to drive a pulley system to rotate the plants on the grow racks, ensuring an even circulation of sunlight for all the plants” (Piccolino 2013; Tsitsimpelis et al. 2016).

2009

Cosmo Park was built in Jakarta, Indonesia. This is a residential development built on top of a 10-storey shopping mall/car park (Guimapang 2019). Cosmo Park could be considered as a proof of concept, for the earlier concepts described as the “supporting structure” by Habraken (Nagore Setién 2011; Martínez Muñoz 2020). “The community comes complete with 78 two-story residences, tennis courts, asphalt roads, a large community pool and greenery.” (Guimapang 2019). Several other projects have also been built integrating green and cultivation areas within buildings (Martínez Muñoz 2020). Other similar examples are The Pinnacle Duxton, Singapore 2009 and The Tembusu, Singapore 2016 (Arc Studio_ 2018). These latter building projects are of similar nature to the “Bioclimatic skyscraper” (Couzens 2012) of Architect Kenneth Yeang (see 1989)

2010

Pasona Urban Farm/Office block was built in Tokyo. A project integrating indoor agriculture within an office building, developed as a retrofit project of a 9-storey office building (Andrews 2013). This is the most holistic integration of indoor farming that has been found in the lifetime of this PhD entailing a building design for humans and plants/crops to coexist indoors. Although, the agricultural produce is not for large/commercial scale production, it is proof of concept for multi-storey vertical farming. This building portraits an integration of two key concepts: “Biophilic Architecture” (see 2005 above) and “Plant Factories” (see 1980 above), where a balance is achieved by compromising on both sides: Biophilic Architecture tends to focus more on the health and well-being of occupants and how this can be improved by integrating greenery in the built environment, whilst “Plants Factories” focus on plant productivity. As a result, in Pasona, plants are less about being just ornaments (biophilic principle) and more about being productive plants (plant factories) but without the need to do it in such a large scale so that plant growing can take place whilst the building is occupied by people too (office block). The space of the building is shared between occupants and plants/crops and the produced crops are used in the canteen and coffee shop of the building.

2011

"Dutch agricultural company, PlantLab uses red and blue LEDs instead of sunlight in their vertical farms and grow plants in completely controlled environments. By giving the plants only blue and red light, PlantLab can avoid heating its plants up needlessly, leaving more energy for growth" (Piccolino 2013)

2012

"Local Garden, North America's first ever VertiCrop farm, was constructed in Vancouver, Canada, shifting sustainable farming and food production practices. VertiCrop, a new technology for growing healthy, natural vegetables in a controlled environment maximizes space usage and eliminates need for pesticides" (Piccolino 2013; Agritecture 2014).

2021

Research work undertaken by Shao et al (2021) integrating vertical farming within an office block, and taking measurements related to indoor air quality. This research has found that the levels of indoor pollution are reduced by integrating vertical farming, hence suggesting the reduction of the levels of air conditioning required to maintain a healthy indoor environment (Shao et al. 2021).

Torreggiani et al (2012) succinctly described the importance of multidisciplinary collaboration for the further development of vertical farms, by highlighting that it urgently requires the integration of several disciplines to be able to bring together the power of nature assisted by high-tech (Torreggiani et al. 2012). Nevertheless, one of the most significant challenges faced by unifying all the disciplines related to the field of vertical farm is the issue around clarity of concept. Vertical farming means different things to different people (Hughes 2018; Butturini and Marcelis 2020). This literature review had to focus also in getting further clarification on the meaning of vertical farms.

To undertake the necessary thorough literature review compulsory for a topic of this scale, a systematic literature review has been developed for this research. The purpose of this systematisation is mainly to fulfil two important goals: (1) to include as many of the important disciplines related to vertical farm, (2) whilst also establishing and maintaining the boundaries of the research, to be able to fit this investigations within the size of a PhD project.

2.4 Systematic Literature Review

As shown on the timeline above, vertical farming is also multifaceted (Ryymin et al. 2020), hence a systematic literature review has been identified as the best approach to include the most relevant factors of this field. Theorising about the focus of the the key concepts of this research was initially challenging due to the number of ramifications that this area can take, hence, an initial superficial review took place. Mainly to gauge the territory of the potential research “routes” and possible related concepts. The words “vertical farms” were cross-referenced with various potential routes: biomimicry, urban farming, urban ecology, architecture, sustainable farming, vertical green systems and urban green areas, growing methods, etc. This initial gathering of information introduced several other concepts that also seemed to be closely related to the term vertical farms.

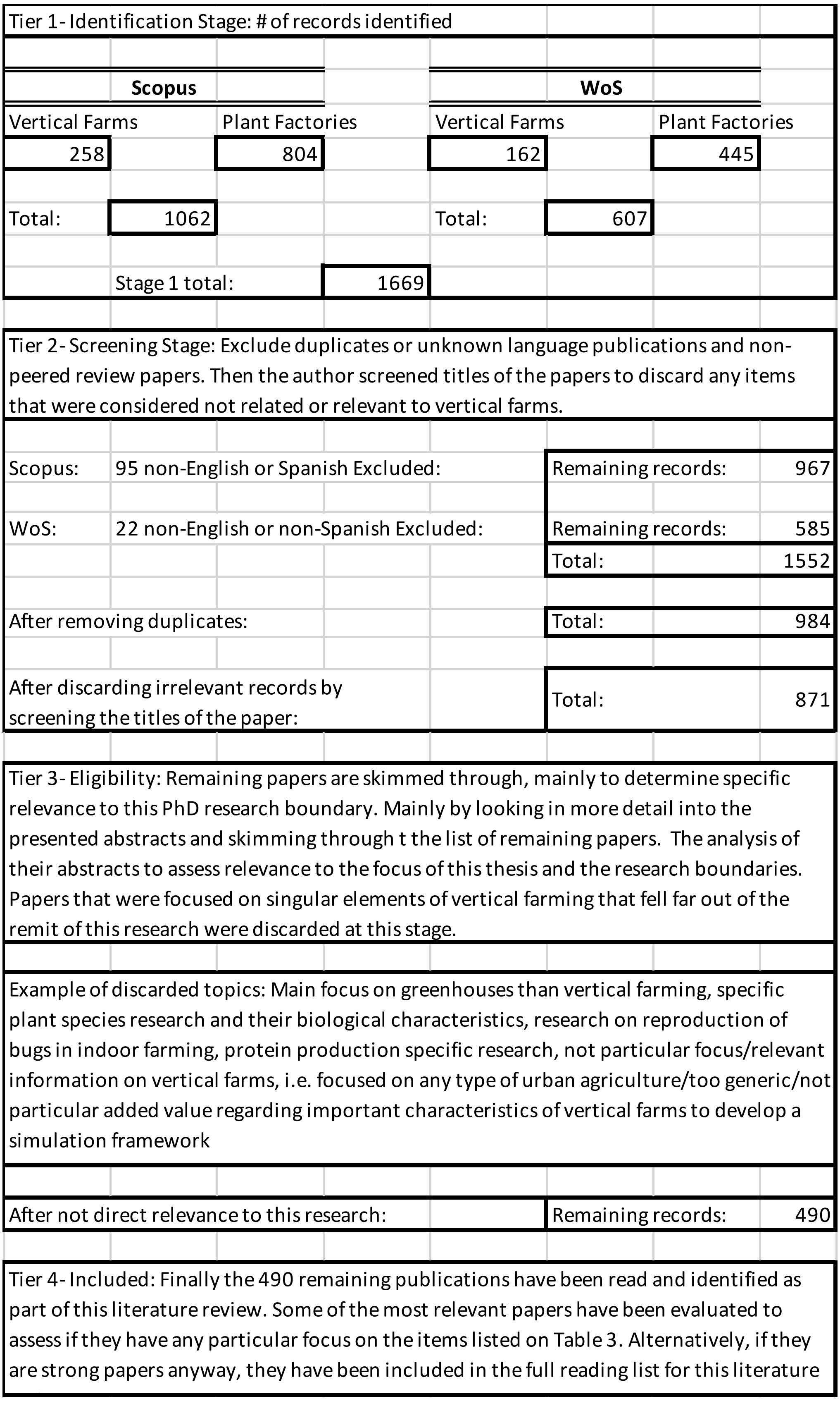
Thus, the chosen approach for this literature review was chosen to follow a similar path as the well-established systematic approach: Moher's 2010 protocol (Moher et al. 2010; Booth et al. 2012; Gough et al. 2012; Mavrigiannaki and Ampatzi 2016). This method follows a four-tier literature review process to provide a robust approach to wide research areas. These four key stages of the review to assess the available literature are: Identification, Screening, Eligibility and Inclusion (see Table 2 for details). There are several literature resources that have been explored and included within the lifetime of this PhD journey, which have gone beyond this initial systematic review. However, at the early-stage of the research, two relevant electronic databases have been chosen to follow this systematic review:

- Scopus and
- Web of Science (WoS)

This process guided the initial approach to the available literature, in order to better select and classify the available resources. To widen the inclusion of the most relevant literature in this investigation, two main terms have been used in this review protocol within the databases: VERTICAL FARM, as well as PLANT FACTORY. The latter has been included due to the fact that several international publications would refer to vertical farms as plant factories (Chen et al. 2013; Kozai 2013a; Chen et al. 2016; Tsitsimpelis et al. 2016).

This initial systematic approach aimed to help to highlight some initial gaps in the body of knowledge of vertical farms. Table 2, presents the outlined structure of the systematic review and further details about the number of publications included in the initial review. Nonetheless, as previously mentioned, other databases beyond Scopus and WoS have also been used during this research journey on vertical farms, this systematic approach did not limit the investigation, but it provided a solid foundation. The overall background research for this thesis has also included books, published doctoral thesis, newspapers articles, specialised magazines, interviews to experts, lectures & seminars, videos/documentaries (such as TED Talks, latest news, etc), amongst others investigative streams.

Table 2. Systematic Literature Review steps and number of papers included



Tier 1- Identification Stage: # of records identified

Scopus		WoS	
Vertical Farms	Plant Factories	Vertical Farms	Plant Factories
258	804	162	445
Total: 1062		Total: 607	

Stage 1 total: 1669

Tier 2- Screening Stage: Exclude duplicates or unknown language publications and non-peered review papers. Then the author screened titles of the papers to discard any items that were considered not related or relevant to vertical farms.

Scopus:	95 non-English or Spanish Excluded:	Remaining records:	967
WoS:	22 non-English or non-Spanish Excluded:	Remaining records:	585
		Total:	1552
After removing duplicates:		Total:	984
After discarding irrelevant records by screening the titles of the paper:		Total:	871

Tier 3- Eligibility: Remaining papers are skimmed through, mainly to determine specific relevance to this PhD research boundary. Mainly by looking in more detail into the presented abstracts and skimming through t the list of remaining papers. The analysis of their abstracts to assess relevance to the focus of this thesis and the research boundaries. Papers that were focused on singular elements of vertical farming that fell far out of the remit of this research were discarded at this stage.

Example of discarded topics: Main focus on greenhouses than vertical farming, specific plant species research and their biological characteristics, research on reproduction of bugs in indoor farming, protein production specific research, not particular focus/relevant information on vertical farms, i.e. focused on any type of urban agriculture/too generic/not particular added value regarding important characteristics of vertical farms to develop a simulation framework

After not direct relevance to this research:	Remaining records:	490

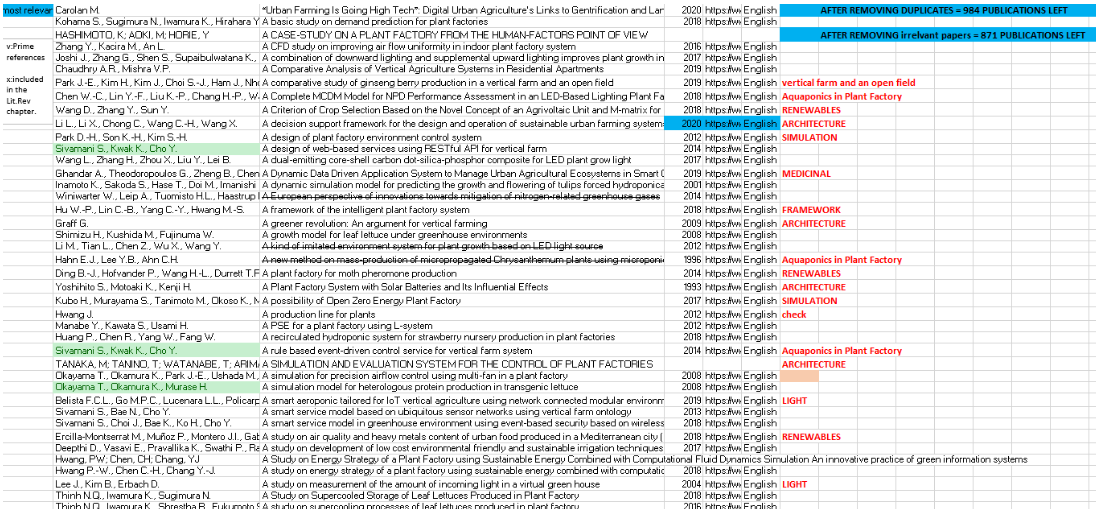
Tier 4- Included: Finally the 490 remaining publications have been read and identified as part of this literature review. Some of the most relevant papers have been evaluated to assess if they have any particular focus on the items listed on Table 3. Alternatively, if they are strong papers anyway, they have been included in the full reading list for this literature

1. Identification (Tier 1):

   This investigation used the results from the two databases aforementioned: Scopus and Web of Science (WoS) as the main databases to some of the most relevant papers. Nevertheless, the overall literature review did not limit itself to these databases alone. A significant amount of vertical farming development also occurred outside the academic realm (i.e. commercial). Therefore, further sources were also appraised, such as books, newspapers, video conferences, etc. Nevertheless, this systematic literature review process allowed the author to cover the majority of academic papers publicly available in the area of vertical farms. The specific terms used for the search in these two database platforms were:
   "vertical farm" OR "vertical farms" OR "vertical farming"
   And a separate search also including publications which included:
   "plant factory" OR "plant factories".

2. Screening (Tier 2):

   Following the process outlined above, all the results are gathered in a spreadsheet (1,062 papers from Scopus and 607 from WoS = Total of 1,669 articles), then Tier 2 consists of discarding the papers that are duplicates, or in a language that is not understood by the reviewer (i.e. all articles in English and Spanish have been considered while other languages have been discarded). In addition, non-peer review papers are excluded and finally some papers were also discarded if they were considered not related or relevant to vertical farms. See sample view of the process described above process in Figure 8). These last few steps were determined by the author of this review, based on the title of the paper (remaining publications = 984).



most relevar	Carolan M.	"Urban Farming Is Going High Tech": Digital Urban Agriculture's Links to Gentrification and Lar	2020	https://ww	English	AFTER REMOVING DUPLICATES = 984 PUBLICATIONS LEFT
	Kohama S., Sugimura N., Iwamura K., Hirahara Y	A basic study on demand prediction for plant factories	2018	https://ww	English	
	HASHIMOTO, K; AOKI, M; HORIE, Y	A CASE-STUDY ON A PLANT FACTORY FROM THE HUMAN-FACTORS POINT OF VIEW				AFTER REMOVING irrelvant papers = 871 PUBLICATIONS LEFT
v:Prime references x:included in the Lit.Rev chapter.	Zhang Y., Kacira M., An L.	A CFD study on improving air flow uniformity in indoor plant factory system	2016	https://ww	English	
	Joshi J., Zhang G., Shen S., Supaibulwatana K.,	A combination of downward lighting and supplemental upward lighting improves plant growth in	2017	https://ww	English	
	Chaudhry A.R., Mishra V.P.	A Comparative Analysis of Vertical Agriculture Systems in Residential Apartments	2019	https://ww	English	
	Park J.-E., Kim H., Kim J., Choi S.-J., Ham J., Nh	A comparative study of ginseng berry production in a vertical farm and an open field	2019	https://ww	English	vertical farm and an open field
	Chen W.-C., Lin Y.-F., Liu K.-P., Chang H.-P., W	A Complete MCDM Model for NPD Performance Assessment in an LED-Based Lighting Plant Fa	2018	https://ww	English	Aquaponics in Plant Factory
	Wang D., Zhang Y., Sun Y.	A Criterion of Crop Selection Based on the Novel Concept of an Agrivoltaic Unit and M-matrix for	2018	https://ww	English	RENEWABLES
	Li L., Li X., Chong C., Wang C.-H., Wang X.	A decision support framework for the design and operation of sustainable urban farming system	2020	https://ww	English	ARCHITECTURE
	Park D.-H., Son K.-H., Kim S.-H.	A design of plant factory environment control system	2012	https://ww	English	SIMULATION
	Sivamani S., Kwak K., Cho Y.	A design of web-based services using RESTful API for vertical farm	2014	https://ww	English	
	Wang L., Zhang H., Zhou X., Liu Y., Lei B.	A dual-emitting core-shell carbon dot-silica-phosphor composite for LED plant grow light	2017	https://ww	English	
	Ghandar A., Theodoropoulos G., Zheng B., Chen	A Dynamic Data Driven Application System to Manage Urban Agricultural Ecosystems in Smart (	2019	https://ww	English	MEDICINAL
	Inamoto K., Sakoda S., Hase T., Doi M., Imanishi	A dynamic simulation model for predicting the growth and flowering of tulips forced hydroponica	2001	https://ww	English	
	Winiwarter W., Leip A., Tuomisto H.L., Haastrup I	~~A European perspective of innovations towards mitigation of nitrogen-related greenhouse gases~~	2014	https://ww	English	
	Hu W.-P., Lin C.-B., Yang C.-Y., Hwang M.-S.	A framework of the intelligent plant factory system	2018	https://ww	English	FRAMEWORK
	Graff G.	A greener revolution: An argument for vertical farming	2009	https://ww	English	ARCHITECTURE
	Shimizu H., Kushida M., Fujinuma W.	A growth model for leaf lettuce under greenhouse environments	2008	https://ww	English	
	Li M., Tian L., Chen Z., Wu X., Wang Y.	~~A kind of imitated environment system for plant growth based on LED light source~~	2012	https://ww	English	
	Hahn E.J., Lee Y.B., Ahn C.H.	~~A new method on mass-production of micropropagated Chrysanthemum plants using microponi~~	1996	https://ww	English	Aquaponics in Plant Factory
	Ding B.-J., Hofvander P., Wang H.-L., Durrett T.F	A plant factory for moth pheromone production	2014	https://ww	English	RENEWABLES
	Yoshihito S., Motoaki K., Kenji H.	A Plant Factory System with Solar Batteries and Its Influential Effects	1993	https://ww	English	ARCHITECTURE
	Kubo H., Murayama S., Tanimoto M., Okoso K., M	A possibility of Open Zero Energy Plant Factory	2017	https://ww	English	SIMULATION
	Hwang J.	A production line for plants	2012	https://ww	English	check
	Manabe Y., Kawata S., Usami H.	A PSE for a plant factory using L-system	2012	https://ww	English	
	Huang P., Chen R., Yang W., Fang W.	A recirculated hydroponic system for strawberry nursery production in plant factories	2018	https://ww	English	
	Sivamani S., Kwak K., Cho Y.	A rule based event-driven control service for vertical farm system	2014	https://ww	English	Aquaponics in Plant Factory
	TANAKA, M; TANINO, T; WATANABE, T; ARIM	A SIMULATION AND EVALUATION SYSTEM FOR THE CONTROL OF PLANT FACTORIES				ARCHITECTURE
	Okayama T., Okamura K., Park J.-E., Ushada M.,	A simulation for precision airflow control using multi-fan in a plant factory	2008	https://ww	English	
	Okayama T., Okamura K., Murase H.	A simulation model for heterologous protein production in transgenic lettuce	2008	https://ww	English	
	Belista F.C.L., Go M.P.C., Lucenara L.L., Policarp	A smart aeroponic tailored for IoT vertical agriculture using network connected modular environm	2019	https://ww	English	LIGHT
	Sivamani S., Bae N., Cho Y.	A smart service model based on ubiquitous sensor networks using vertical farm ontology	2013	https://ww	English	
	Sivamani S., Choi J., Bae K., Ko H., Cho Y.	A smart service model in greenhouse environment using event-based security based on wireless	2018	https://ww	English	
	Ercilla-Montserrat M., Muñoz P., Montero J.I., Gab	A study on air quality and heavy metals content of urban food produced in a Mediterranean city (	2018	https://ww	English	RENEWABLES
	Deepthi D., Vasavi E., Pravallika K., Swathi P., Ra	A study on development of low cost environmental friendly and sustainable irrigation techniques	2017	https://ww	English	
	Hwang, PW; Chen, CH; Chang, YJ	A Study on Energy Strategy of a Plant Factory using Sustainable Energy Combined with Computational Fluid Dynamics Simulation An innovative practice of green information systems				
	Hwang P.-W., Chen C.-H., Chang Y.-J.	A study on energy strategy of a plant factory using sustainable energy combined with computatic	2018	https://ww	English	
	Lee J., Kim B., Erbach D.	A study on measurement of the amount of incoming light in a virtual green house	2004	https://ww	English	LIGHT
	Thinh N.Q., Iwamura K., Sugimura N.	A Study on Supercooled Storage of Leaf Lettuces Produced in Plant Factory	2018	https://ww	English	
	Thinh N.Q., Iwamura K., Shrestha B., Fukumoto	A study on supercooling processes of leaf lettuces produced in plant factory	2016	https://ww	English	

Figure 8. Sample view of the matrix Tiers 2-3 (stages) of the selection process of papers for inclusion in the literature review.

3. Eligibility (Tier 3):

Papers remaining after Tier 2 were further assessed by browsing rapidly through them and filtering the ones that were sufficiently relevant according to the aims of this PhD project and therefore determined how many were chosen for further examination (871 publications remained after this). The author of this investigation developed a physical diagram with some of the key papers from this process (see Figure 9). This step aimed to pinpoint the most relevant parameters in the area of vertical farms (and plant factories) and to find a thread amongst the different concepts used across the related fields. This aided the selection of the main classifying parameters. The schematic created (Figure 9), helped to identify some of the main papers that focus on the parameters outlined in Table 3, presented in Tier 4 below.

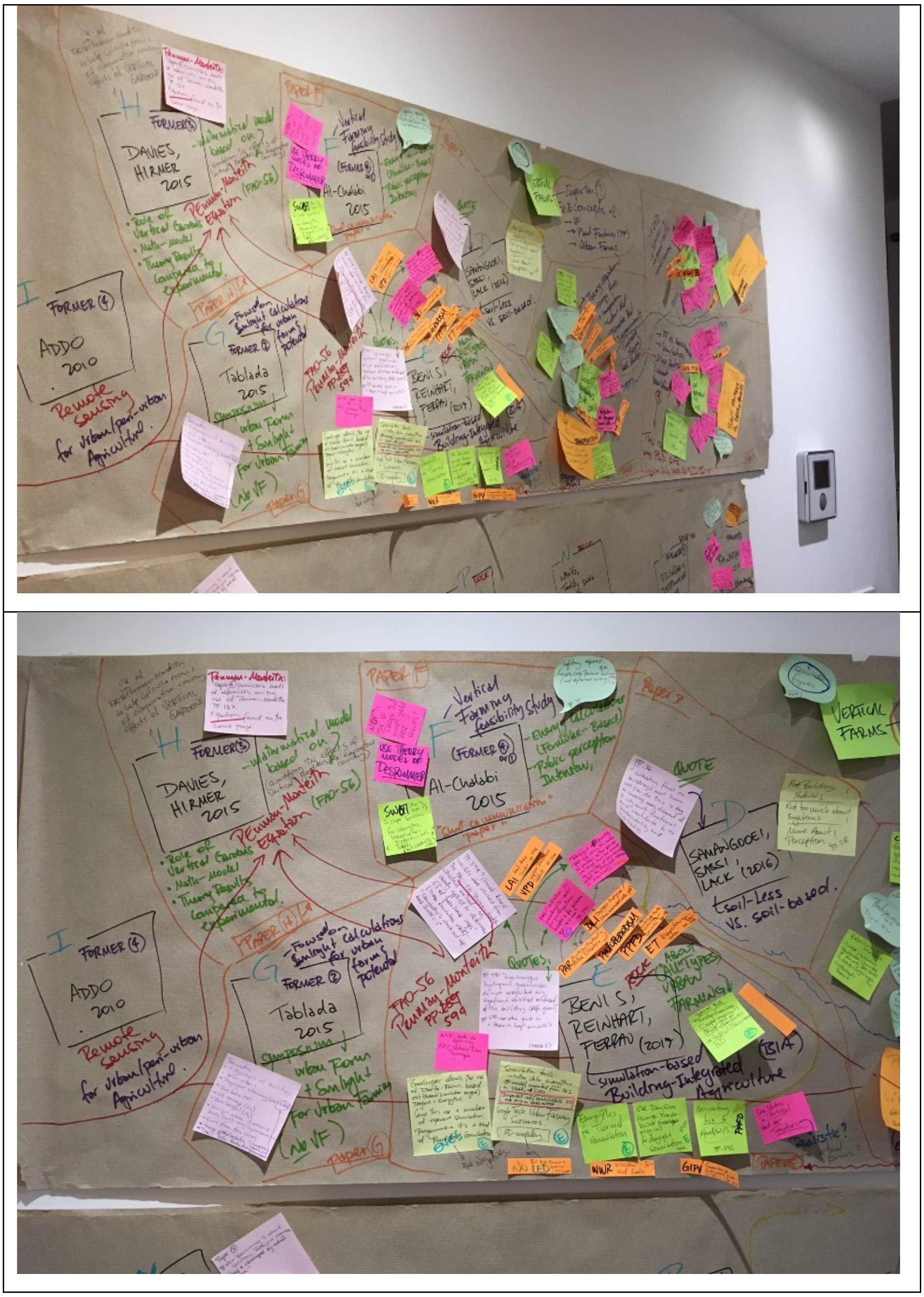


Figure 9. Diagrammatic charts to analyse selected papers for filtering selection characteristics

4. Inclusion (Tier 4):

   Following the tier-stage process described above (also detailed in the Table 2), the final number of papers that have been identified from Scopus and Web of Science for this main part of the literature review are: 490. In order to narrow this selection down to the final relevant detailed reading and analysis, the characteristics highlighted in the Table 3 below were considered. The focus parameters included in the table were based on findings gathered in Tier 3.

Table 3. Focus parameters

Types of vertical farming / classification name		**Themes**	**Methods**
Acronym	Description	Description	Description
VF	Vertical Farming	System optimisation, Thermal	Review Experimental
PF	Plant Factories	Design Vegetation	Simulation/Modelling Experimental + Simulation/Modelling
CEA	Controlled Env.	Humidity Nutrients	Survey/Questionnaire
BIA	Agriculture Building Integrated Agriculture	Growing medium (Hydroponics, Aquaponics, Aeroponics, Soil-based)	

Based on the selection process above, the papers that were related to the concepts outlined in Table 3 were therefore selected to draw a wealth of information in the area of vertical farming (and related concepts) that will be described below in the sections below.

2.5 Green Walls vs Vertical Farm.

As highlighted in the introduction chapter (Chapter 1) there is an urgent need to make cities more sustainable and in general greener (Howard 1965; Lim and Liu 2010). Although sustainability principles are increasingly used to guide neighbourhood development (Sharifi 2016), urban sprawl is creating a number of negative issues in cities, such as air and water pollution, increased noise levels, reduced vegetation and consequently increased UHI and global warming (Alexandri and Jones 2008; Safikhani et al. 2014).

However, cities can also hold a key for the solutions to these problems, “cities as solutions” (Lim and Liu 2010). There is significant research evidence in the published literature on the benefit of the previously mentioned green elements within cities, such as the long-standing concept of urban parks and allotments (Orsini et al. 2013; Seguí et al. 2017). Additionally, there are also somewhat more modern building greening methods such as green walls and green roofs, which sometimes overlap with agriculture (Alexandri and Jones 2008; Silva et al. 2015; Bustami et al. 2018). These areas have been significantly well researched throughout several decades and numerous publications provide evidence supporting that these greenery elements and systems have a significant effect in mitigating Urban Heat Island effect (UHI) (Alexandri and Jones 2008; Cheng et al. 2015) and several of the previously mentioned issues (Safikhani et al. 2014; Sun et al. 2014).

These green wall/roofs systems have been relatively well investigated and spread across different cities around the world (Alexandri and Jones 2008; Koyama et al. 2013; Sun et al. 2014; Silva et al. 2015; Solcerova et al. 2017). In addition, there is significant published research evidence showcasing the benefits of having green elements integrated within cities (Safikhani et al. 2014; Thuring and Dunnett 2014; Wolch et al. 2014; Solcerova et al. 2017; Xing et al. 2019). “Applying vertical greenery systems not only reduce temperature, but also have many economic, environmental and social benefits” (Safikhani et al. 2014). The research community has unveiled large amount of data on how these systems work and perform under different conditions (Alexandri and Jones 2008; Koyama et al. 2013; Brown and Lundholm 2015). For instance, interesting advancement has been done on the thermal properties of green walls/roofs in order to insulate a building more effectively (Sun et al. 2014), as well as research done in how this green elements add to counteract pollution, acoustic contamination, enriching urban micro-climate conditions, etc (Safikhani et al. 2014). Furthermore, Safikhani et al (2014) provide an exhaustive list of useful research studies and real-life examples of green walls. However, they describe in this paper that green roofs “are more extensively researched than green walls, or vertical greenery as the author calls them”. Building on this issue, vertical farms are far behind these two methods of urban greening (green walls and roofs) and there is an urgent need to move them forward.

However, some of the areas of study in green wall/roofs systems are less popular in the research community than others (see Table 4). Therefore, an initial comparison based on the number of publications related to several fields linked to urban green and agricultural elements. Table 4 presents the topics that have been compared on this search. The Boolean operator asterisk (*) was used to ensure that the search will include related variations of the specific key words, which included the comparison of a number of publications related to green elements and agriculture of cities.

Table 4. Number of publications per topic comparing Scopus and WoS

Topic	**Scopus**	**WoS**
"green roof*"	3,099	2,914
"urban parks"	2,934	2,943
"urban agriculture"	2,880	2,803
"urban farm*"	938	731
"green wall*"	621	547
"vertical farm*"	331	272

In the above literature, there is evidence supporting that greenery in cities help to mitigate Urban Heat Island (UHI) effect (Alexandri and Jones 2008; Cheng et al. 2015) and various other issues previously mentioned in this chapter (Safikhani et al. 2014; Sun et al. 2014). Table 4 shows that based on the publications available on these two databases, the topic "green roof" is the most popular. This green element integrated into the built environment has been significantly well investigated across different cities and countries (Alexandri and Jones 2008; Sun et al. 2014; Thuring and Dunnett 2014; Brown and Lundholm 2015; Silva et al. 2015; Solcerova et al. 2017). The topics of "urban parks" and "urban agriculture" are just below "green roof" in terms of extensive research.

Thereafter, there is a significant drop in the number of publications of fields related to green elements and agriculture after the top three most popular topics mentioned above. The next most popular topic placed fourth place in Table 4 is "urban farm", which accounts for three times less popularity compared to the topic above it, publications such as Viljoen et al. (2005); Broyles (2008); Torreggiani et al. (2012); Orsini et al. (2013); Thomaier et al. (2014); Ward R et al. (2018) focus on the history, development and benefits of urban farming. In occasions these publications reflect how this concept overlaps with some of the other concepts included in Table 4 (Viljoen et al. 2005; Benis et al. 2018). Similarly, on the topic of "green walls", several research publications related to this topic overlap with other concepts on this table, this investigation found in particular several connections between the topics "green walls" and "green roofs" (Alexandri and Jones 2008; Sun et al. 2014; Silva et al. 2015; Xing et al. 2019). Further relevant articles in the area of green walls, such as Koyama et al. (2013); Pérez et al. (2014); Safikhani et al. (2014); Solcerova et al. (2017); and Bustami et al. (2018) and Akinwolemiwa et al. (2015, 2018) demonstrate with scientific studies the important benefits of this greening urban element, related to the problems highlighted at the beginning of this introduction. For instance, "applying vertical greenery systems not only reduce temperature, but also have many economic, environmental and social benefits" (Safikhani et al. 2014). The research community has unveiled large amounts of data on how these systems work and perform under different conditions (Alexandri and Jones 2008; Koyama et al. 2013; Akinwolemiwa and Gwilliam 2015; Brown and Lundholm 2015).

Significant advances have been reflected on academic publications regarding the various achievements on the thermal properties of green walls/roofs in order to insulate a building more effectively (Sun et al. 2014; Bustami et al. 2018) or to achieve cooling thermal comfort in hot climates and improve energy efficiency (Akinwolemiwa and Gwilliam 2015; Akinwolemiwa et al. 2018; Xing et al. 2019). Furthermore, research has been undertaken to evaluate the positive impact of these green elements on tackling pollution, acoustic contamination, enriching urban micro-climate conditions, etc (Alexandri and Jones 2008; Safikhani et al. 2014; Bustami et al. 2018). In particular, research publications such as Safikhani et al (2014) and Bustami et al (2018), provide an exhaustive list of research studies including simulation work, real-life monitoring case studies of these green urban elements. Various authors mentioned above have published their own exhaustive literature review on green walls and green roofs. The number of benefits provided by façade-integration vegetation has attracted significant amount of interest in the research world as shown above. Nevertheless, green walls are usually integrated with the focus on the aesthetics only, few buildings actually integrate green walls with the specific purpose of improving the energy efficiency (Susorova and Bahrami 2013). On a similar note, Safikhani et al (2014) agree that the area of green walls is still under-researched and this statement concurs with the statistics presented in Table 4. Safikhani et all (2014) explicitly make the remark in their publication that the area of "green walls" is significantly less explored than the area of "green roofs".

Adding to the previous argument and taking into consideration that other academic authors also acknowledged the fact that the area of green walls has been under-researched, especially when compared to its counterparts presented in Table 4, there is yet another intriguing field that has been even more under-represented in the academic literature. With approximately half the number of publications compared to green walls (see Table 4), the topic of "vertical farms" stands at the bottom of the classification of topics presented in Table 4 related to green and agricultural elements of urbanised areas. Therefore, the topic of this thesis has been subsequently focused on the topic of vertical farms.

2.6 The Issue of Defining Vertical Farm.

There is not an agreed definition of the term Vertical Farm (Hughes 2018; Butturini and Marcelis 2020) alternative sources define this term differently. Thus, the definition provided below is the conclusion of the author of this thesis based on the extensive literature review and engagement with the vertical farming community:

> *As the name suggests, vertical farming is the concept of growing food or plants vertically. This cultivation method is considered to be an alternative agricultural practice. Various approaches can be used to achieve verticality. On one side of the spectrum, this can be accomplished by stacking plant pots, containers or trays to grow various layers of plants or food above each other. On the other end of the spectrum, vertical growing can be achieved at a building scale, where the growing of plants takes place on any number of levels of a multi-storey building. Both ends of the spectrum can be deployed at small or large scale. However, the financial implication of either approach must be carefully considered and planned in advance, since the cost-benefit of this practice has not been completely proven yet. Independent of the method used to achieve vertical farming, the important element is to provide plants with all the necessary characteristics for them to thrive and ensure quality produce. The main requirements being: a growing medium, nutrients, water, optimum air quality and light.*
>
> *Other important characteristics particularly relevant to establish clear differences between the various types of vertical farms are: the type of lighting (natural or artificial), environmental controls (natural ventilation or mechanical) and location (urban or rural).*

Vertical farms can follow either of the characteristics above, as long as the right environment is provided for the plants to grow.

Returning to the TWO initial boundary fields established earlier for this investigation:

1. **Architecture and Urbanism.**
2. **Urban Agriculture and Food Production.**

The particular topic of **Vertical Farms** does fall neatly within the overlapping area of these TWO initially outlined boundaries of research (previously shown in figure 2). At an early stage of this investigation, it became evident that vertical farming is a highly multidisciplinary field (Despommier 2010; Gillott et al. 2014; Al-Chalabi 2015; Sarkar and Majumder 2015; Shao et al. 2016) and there are several closely related variations of the concept (i.e. Plant Factories, Building Integrated Agriculture and other concepts, which will be further described later in this chapter). One common aspect across most, if not all, references and networking events related to this field, is the agreement on the issue that this is an area still considered to be in its infancy. This particular issue is highlighted by various authors in the field (Higgins 2016; Benis et al. 2017b; Graamans et al. 2018; Khalil and Wahhab 2020), as well as being a central topic of conversation in networking events and seminars (Farquhar 2020; Storey et al. 2020; Zimmerman-Loessl et al. 2020).

Popular research databases can provide valuable historical information related to various topics of publications, particularly in terms of quantity and types of articles published. These databases often have records of publications going back several decades. For instance, Figure 11, provides an initial idea of the level of publications available in the area of vertical farms, which had an incremental acceleration during the past 4 years. As a result, the lifetime of this PhD has witnessed a significant change in this area. Thus, this investigation has been a dynamic research project, throughout the years and alongside the simulation work for his PhD, the author has also been an active member of the vertical farming research community, attending seminars, conferences, staying up-to-date with new developments and advances. At present this a significantly fast-paced research area, as a result, this literature review has been populated in parallel with all the other activities of this research project, in order to stay on top of this constantly evolving field.

Figure 11 was developed using data gathered from the two databases used for the systematic literature review: Scopus and Web of Science (WoS). Similar to the results previously presented in Table 4, the Boolean operator asterisk (*) was also used in this investigation, to ensure that the search included as many related variations as possible of the words "vertical farm*". The results from Scopus are marked in blue in the bar chart and WoS is marked in orange. Both the table and the bar chart represent the number of publications per year.

As it can be seen in Figure 11, the number of records for "vertical farm*" in Scopus increased from 13 publications in 2015, to 87 in 2020. WoS follows a similar incremental pattern: 12 records in 2015 and 59 in 2020. Figure 12 provides further historic context of the incremental growth on the number of publications in the area of vertical farms. In this occasion, the data presented in the graph below is only based on publications from Scopus, since WoS followed a similar pattern. Figure 12, depicts a close-up of this accelerating period witnessed during the last few years. Publications related to vertical farms were experiencing a gradual increase from 2008 until 2016 where a noticeable acceleration has occurred during the last 4 years.

"vertical farm*"

Number of publications per year

Year	Scopus	WoS
2005	0	0
2006	0	0
2007	0	0
2008	6	3
2009	3	2
2010	2	4
2011	6	7
2012	8	2
2013	8	8
2014	16	6
2015	13	12
2016	15	11
2017	34	22
2018	58	33
2019	63	42
2020	87	59

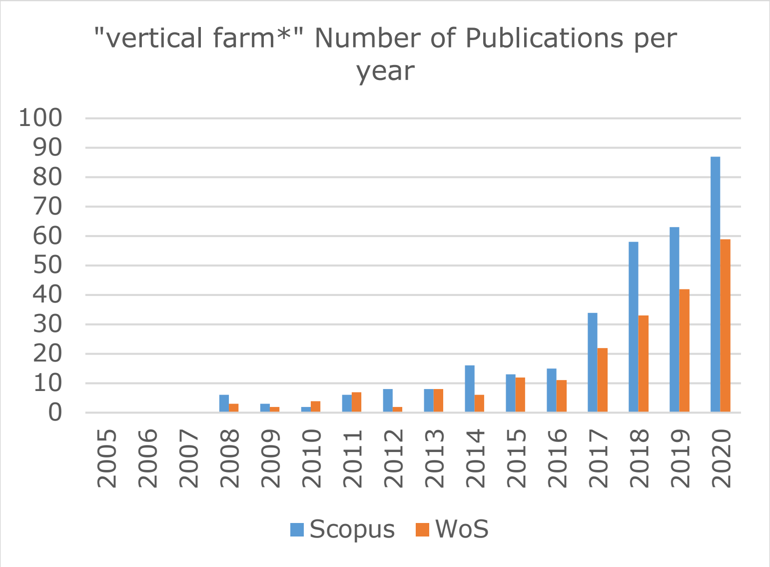


Figure 10. Number of publications per year, comparing two databases: Scopus and Web of Science

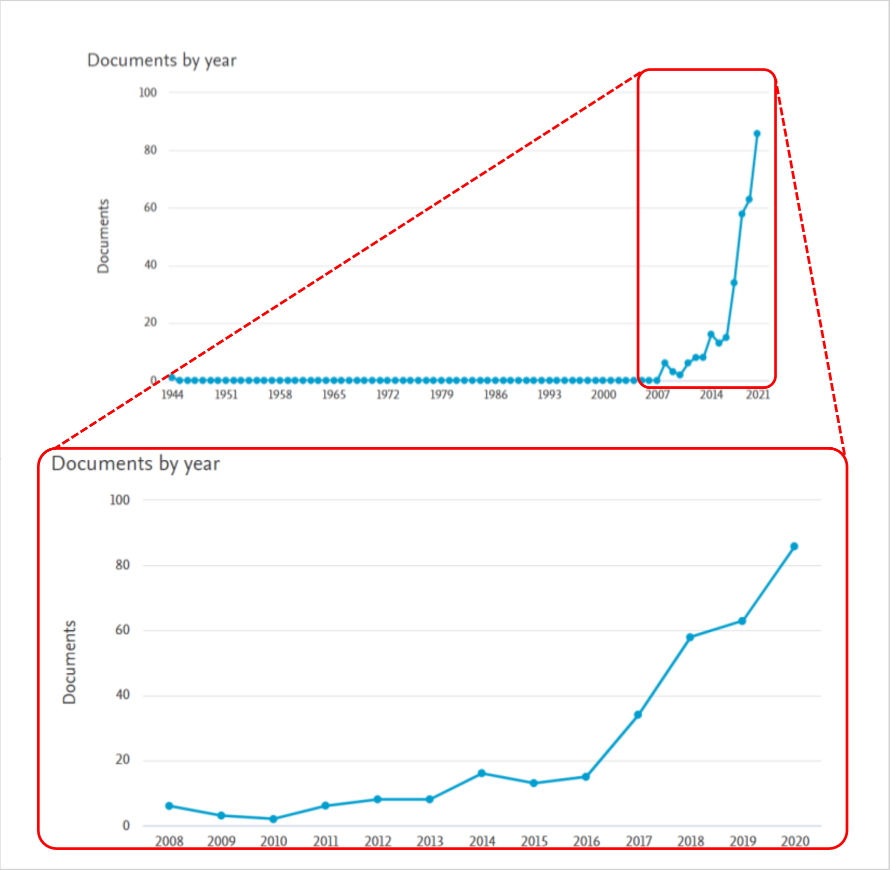


Figure 11. Scopus Statistics for number of publications per year

Some researchers define vertical farm as a "new method of modern agriculture […] producing food in a multi-storey building or tower in controlled environmental conditions." (Kalantari et al. 2018). Despommier (2014) defines vertical farms as a form of controlled environment agriculture, or CEA. Others attach negative connotations to the term vertical farms, such as Thomaier et al (2014) who describe it as "the most far-reaching vision of farming in and on urban buildings". In their publication the authors associate the design of vertical farms only with futuristics multilevel urban structure that solely serves the purpose of food growing (Thomaier et al. 2014). Nevertheless, the cited work by Thomaier et al based their arguments on one version of vertical farms, which is also known as 'Zero-Acreage Farming', or ZFarming.

In general, the literature available on vertical farms is rather fragmented across the world, often contradicted. It comes across as a concept that is not clearly understood in terms of cohesiveness between all the different references, despite the fact that there are several examples of various types of vertical farms around the world. Different stakeholders describe concepts related to vertical farms based on their own agendas, often without the consideration of the bigger picture, i.e. the fact that vertical farming comprises a number of relevant disciplines that interact with each other. Overall, there is a common lack of clarity of the terminology used in this field. Therefore, aiming to establish the most sensible foundations for this research, this investigation starts with the scrutiny of the terms: "vertical farms" and "vertical farming".

However, during this process, it has been found that even by bringing together as many published references as possible, both from academia and industry, it is evident that attempting to find a homogenous language in this field is a complex issue. This is due to the non-standardised manner by which this topic is documented. It is difficult to find common concepts and descriptions across the board. This complexity was also highlighted also by Hughes (2018).

Therefore, it was identified at an early stage of the literature review that, first of all, clarity must be established between these two basic concepts:

- *Vertical Farm*: As a *noun*
- *Vertical Farming*: As an *activity*

Across the literature these two terms seem to be merged, as if the *noun* were the same as the *activity*. If the vertical farming community does not have a clear understanding of this basic difference, then it is unsurprising that there is a lack of cohesiveness in the development of vertical farms around the world. There is little evidence of collaborative work towards the improvement of this practice. By establishing clarity of the fundamental concepts associated to vertical farms, this investigation aims to encourage better future communication amongst researchers and industry partners, towards the further improving of the efficiency of vertical farms. Therefore, this thesis aims to find some clarity on the most appropriate context for both terms: "vertical farms" and "vertical farming", in order to achieve consistency. By establishing congruency at the foundation of this research, this project aims to structure a replicable methodology of framework to analyse vertical farms in order to make them more efficient, sustainable and also available to more people.

One simple root of the problem to the misunderstanding amongst the two terms mentioned above can potentially lay with the fact that they are both commonly abbreviated as VF, whether people are referring to the verb or the noun. The scientist Dickson Despommier (commonly referred to as "the father of modern vertical farms" (Franchini 2016)) often in his publications uses the acronym VF to denote vertical farms (or VFs) – i.e. the *noun*. However, in a published section for the Thomson & Kaplan's Encyclopaedia for Food and agriculture (Despommier 2014) he describes VFs to be a form of Controlled Environment Agriculture (CEA)– which is a concept that is directly linked to vertical farms, but CEA is an *activity*, not a *noun*. Continuing with this interesting reference (Thomson & Kaplan's Encyclopaedia for Food and agriculture (Despommier 2014)), Despommier here also describes how by the year 2010, when he published his book on vertical farms (Despommier 2010), "there were no real cases of them" [vertical farms]. After the publication of his book, a number of vertical farms then became a reality across the world initially in "Korea, Japan, Singapore and the US" (Despommier 2014). Kalantari et al. (2017a) begin their article referencing Despommier's work, however they use the acronym VF for the *activity*, i.e. vertical farming, where they present vertical farming (VF) as the "answer" to solve issues related to food production challenges due to growing population, earth erosion, etc. Similarly, in their following paper Kalantari et al. (2018) defines the "Vertical Farming (VF) initiative [...] as a new method of modern agriculture [...] the practice of producing food in multi-storey building or tower in controlled environment conditions". Furthermore, Banerjee and Adenaeuer (2014a) refer to "Vertical Farming (VF) [as a] system of commercial farming whereby plants, animals, fungi and other life forms are cultivated" (Banerjee and Adenaeuer 2014a).

So, in the continuous effort to bring some cohesiveness into this topic, this research will **establish the use of the acronym VF for the activity (vertical farming), not for the noun (vertical farm).** Two main reasons helped to finally established this: 1) more published authors tend to use VF for the *activity* of farming and 2) one of the largest international associations in this area is the Association for Vertical Farming, its acronym is AVF. This organisation produces a large number of publications related

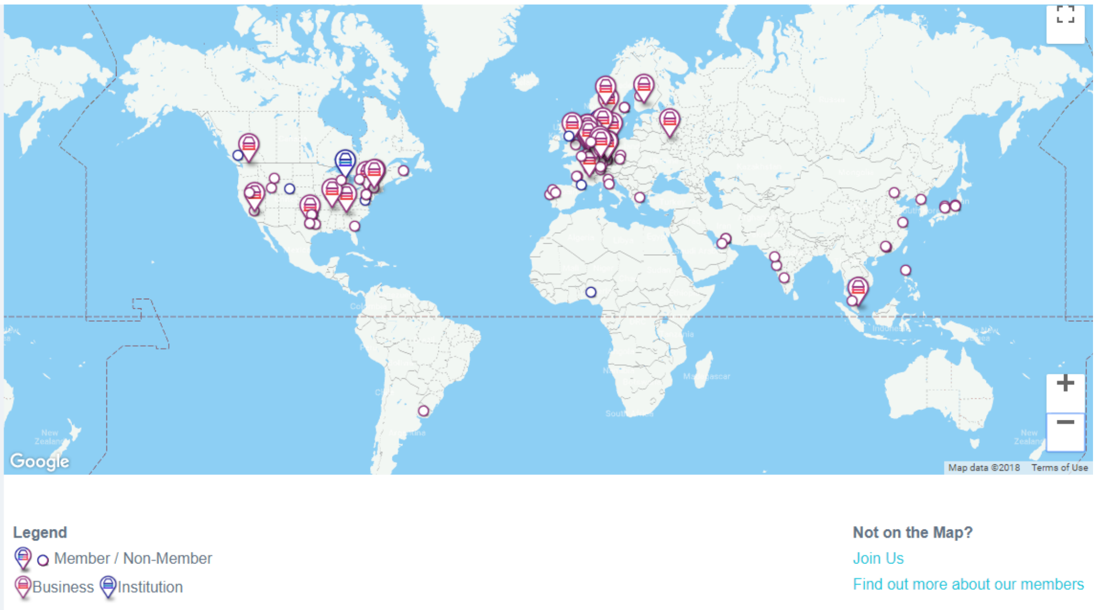


Figure 12. AVF world map of vertical farms associations and AVF members. Source: AVF website.

to VF across the world. They also connect the international VF community through their annual summits and several other related events (Figure 13).

Moving into the basic definitions of the concept of VF, this process should begin by highlighting that some authors provide their own concept or definition, albeit not usually coinciding. For instance, Benke and Tomkins (2017), Despommier (2009), Kalantari et al (2018), Al-Chalabi (2015) and Fischetti (2008) claim that *vertical farming* is a *model*, or an *initiative*, where crops are grown in high-rise, multi-storeys buildings. Therefore, their concept suggest that vertical farms are limited to high-rise buildings. Some of these authors go even further to specify that it is an urban farming method (Al-Chalabi, 2015 and Fishchetti, 2008), which suggests that it can only exist in cities. However, there is evidence that VF is an agricultural practice that is not necessarily undertaken in high-rise buildings, nor exclusive to urban areas. Frediani (2010) published his work and research on the development of the first vertical farm in the UK. This was located at Paignton Zoo. They have chosen VF as their agricultural method to produce lettuces (and other green leaves) destined to feed the zoo animals. This particular example was not based in a high-rise building and it is located in a rather rural context. There are a number of other examples of vertical farming that follow similar characteristics. Frediani (2010) defines the method used for this scenario a **High Density Vertical Growing facility (HDVG),** which can be considered a form of **Controlled Environment Agriculture (CEA).** As previously mentioned, exploration into vertical farms will promptly lead you into a number of other closely related agricultural methods, such as **Controlled Environment Agriculture (CEA),** Building Integrated Agriculture and more. One term that has been imminently linked to vertical farms is the **Plant Factory (PF)** concept. These concepts will be further discussed in section 2.6 of this chapter.

2.7 Current concept of Vertical Farms

The current concept of vertical farms gained new momentum particularly in 1999, with the theoretical work undertaken by Dr Dickson Despommier. He is a Professor of Environmental Health Sciences and Microbiology at Columbia University, New York. Dr Despommier explains: "the concept of the vertical farm arose in my classroom in 1999 as a theoretical construct as to how to deal with a wide variety of environmental issues." (Plan 2B Green 2011). There is evidence of some advances in the area of what is currently known as VF before 1999 (Plan 2B Green 2011); however, major theoretical boost in this area only occurred with Dr Despommier's publications and designs (Despommier 1999, 2009), as well as his work in collaboration with colleague Fischetti (2008).

The decade following Dr Despommier's work/publications witnessed a dramatic increase in the number of 'real-life' vertical farms developed, also referred to as vertical agriculture, and occasionally denoted as plant factories (Yang 2014). Furthermore, this number continues to increase exponentially and more vertical farm projects are coming to life (Yang 2014; Association for Vertical Farming 2016). Despite existing obstacles to develop vertical farms as Dr Despommier described in his publications, significant progress has taken place in this area. Perhaps not quite as large as the ones suggested by him, but projects of 3- to 5-storey facilities can be found in a number of countries around the world, a few perhaps larger (Association for Vertical Farming 2016). Table 5 shows ten initial examples of some openly publicised vertical farms projects.

Table 5. A small sample of vertical farms around the world

Country	City	Project Name/Organisation	Size/Type
Korea	Suwon	Rural Development Agency	3-storeys
Japan	Kyoto	Nuvege	Plant Factory
Singapore	Lim Chu Kang	Sky Greens	4-storeys
USA	New Jersey	AeroFarms	2,800m2 warehouse
Sweden	Linkoping	Plantagon *(Never built)	17-storeys
USA	Chicago	The Plant	4-storeys
USA	Wyoming	Vertical Harvest	3-storeys
USA	Milwaukee	Growing Power	5-storeys
Holland	Hertogenbosch	PlantLab	Underground Farm
China	Shanghai	Agricultural Science and Technology Co.	Plant Factory

It is not always easy to get access to the details of existing vertical farms. Nevertheless, to further expand the number of vertical farms presented in Table 5, the list below provides further examples of other vertical farms found during this literature review. These are a few examples of organisations that have shared enough details to be included in this review. During this research, it has been found that vertical farms often operate under strict confidentiality, due to commercial sensitivity, which can hinder knowledge-sharing.

- **SPREAD Co Ltd:** Spread has been the subsidiary company originating from the Trade Group, which is the Japanese market leader on fresh produce distribution. For many years they have been involved in this business from the production stage to the sales (Kozai et al. 2016a). Using this valuable experience SPREAD was created with the construction of the Kameoka Plant, "the world's largest plant factory in terms of production" (21,000 heads of lettuce per day) (Kozai et al. 2016a). It is one of the few plant factories to achieve profitability and it aims to upgrade to also become a highly automated vegetable factory (ditto).

- **PlantLab:** Originally from the Netherlands, also with base in the US. They have developed their own patented original system to grow in close environment, Plant Production Units (PPU). They use LED lights from the company Illumitex and proprietary plants algorithm to calculate air, water, nutrition and control solutions. The company claims to have control on crop growth, crop yield, harvest planning, nutritional content, taste, etc. They focus on "Plant Physiology" knowledge (PlantLab 2018).

- **Philips:** They have an owned PFAL facility in Eindhoven, the Netherlands, and also supply grow lights to multiple large-scale PFALs in Japan, North America and Europe (Philips 2019).
- **Growing Underground:** London-based underground PFAL. Growing micro-greens and some leafy greens, with a multi-layered hydroponic system (Jans-Singh et al. 2019).

- **GrowUp Farms:** They focus on growing micro-greens, baby leaf salads and herbs, including fish produce, using an aquaponics system. It uses Philips Green Power LED Production Modules. Further details of this site can be found in the Case Study chapter.

- **NiceGreen:** The business model of this vertical farm is not to sell the raw produced directly to the consumer, but to grow leafy greens required for the products they sell, such as processed food, cosmetics, etc. (Kozai et al. 2016a). Company based in Taiwan.

- **Farmbox Green:** Based in the USA. They started with aeroponics and LED lights in 2011, thereafter expanding to also hydroponic growing in a 70m^2 facility, in 2013. They have a climate-controlled facility and use the "latest lighting technologies". The shared details on the lighting specifications used: 17 W white TLED and Gen 1 Dark

Red/Blue Philips GreenPower Production Modules. Growing more than 15 varieties of microgreens and herbs. (Farmbox Green 2019).

2.8 Scoping collaborative case studies

As it can be seen above, samples of vertical farms can be observed around the globe. Some countries in particular have shown higher ambition to lead the research industry of vertical farms, the most noticeable in the literature are Japan, China, Singapore, Holland and the US. As described by Liu and Teng: "Japan, China and Taiwan are the countries with the greatest concentration and growth of plant factories. Japan currently leads the plant factory market with an estimated 210 plant factories in operation [it is projected that] the market for plant factories can grow to $105 billion Yen in Japan alone. Taiwan and China have around 140 plant factories each" (Liu and Teng 2017). In addition, it has been reported that the majority of Asian plant factories (or vertical farms) are clustered in 4 countries: Japan, China, South Korea and Taiwan (Kalantari et al. 2017a). This represents over 40% of these enterprises, which make up for these countries' pivotal plant factories industries. (Newbean Capital and Singapore Farming 2016).

The above information found during the literature review, assisted to inform the focus of the scoping of the case studies. During the first year of this PhD, the initial aim was to find active vertical farms that would be willing to collaborate and share data. The original ambition was to have at least two case studies that could be compared (more if possible). Therefore, the author of this PhD contacted several stakeholders to gauge the potential possibilities (the list of some of the stakeholders contacted can be found in Appendix 1). It was deemed valuable also if there was a possibility to have the option to gain knowledge from both, national and international scenarios. Various vertical farms sites in the UK were visited by the author of this PhD. Furthermore, in an attempt to gain also international case studies, the information found in literature provided supporting statements to choose one of the countries mentioned above: Japan, China, Singapore, Holland, US, South Korea or Taiwan.

A Newton Fund Call opened, to apply for PhD mobility grants. The call was to create collaborative links between the UK and China. Since China was one of the aforementioned countries, an application for this Newton Fund was submitted and successfully granted. Further details of the scoping study and activities of all the considered case studies will be described in Chapters 5 and 6.

Table 6 below provides a compilation of various vertical farms found during the literature review. The table was elaborated in an attempt to compare the various characteristics of the different vertical farms, such as the type of growing method (hydroponic, aquaponic, etc), type of lighting, size, etc. Nevertheless, the blank cells on the table represents data that was not available, i.e. that lack of data in the literature, which is the reflection of the lack of cohesive reporting and data-sharing of vertical farms around the world.

Table 6. Classification and recording of vertical farms (empirical) – Blank cells represent the lack of available data

	Summary of all the vertical farms presented in this review																							
	Name	Country	City	Year	Type of vertical farm					Classification							Size			Current Status		Nature of project		simulat
					Hydroponic	Aquaponic	Aeroponic	Soil-based	Other	Vertical Farm	Natural light	Artificial light	Plant Factory	CEA	PFAL	Other	m2 (floor area	multi-layered	storeys	Running	Close	Commercial	Academic	
1	PlantLab	Netherlands (HQ) and venue in USA	Den Bosch	2011/2014	▨		▨					▨			▨		6,000		3	yes (in2016)				
2	MIRAI	Japan and Rusia		2016											▨									
3	Philips (own PFAL)	Netherlands	Eindhoven	check more info											▨									
4	SPREAD Co Ltd	Japan	Kyoto	2006																				
5	GrowUp Farms	UK	London	2013		▨												▨						
6	Growing Underground	UK	London		▨													▨						
7	NiceGreen	Taiwan																						
8	Farmbox Greens	USA	Seattle, Washington	2011	▨		▨										70			yes (in2016)				
9	LettUs Grow	UK	Bristol																					
10	V-Farming (Hydrogardens	UK	Coventry																					
11	Paigton Zoo VF (Closed)	UK	Paigton																					
12	Grow Bristol	UK	Bristol																					
13	Rural Development Agency	Korea	Suwon																					
4	Nuvege	Japan	Kyoto	2011	▨								▨											
15	Sky Greens	Singapore	Lim Chu Kang	2009			▨			▨	▨	▨												
16	AeroFarms	USA	New Jersey																					
17	The Plant	USA	Chicago	2013	▨	▨				▨	▨	▨							3					
18	Vertical Harvest	USA	Wyoming																3					
19	Growing Power	USA	Milwaukee																					
20	PlantLab	Holland	Hertogenbosch																					
21	Agricultural Science and T	China	Shanghai																					
22	Pasona Urban Farm	Japan	Kyoto	2010															9	yes (in2018)		Office Building		
23	VertiCrop TM	Vancouver	Canada	2009	▨						▨	▨												
24	Republic of South Korea VF		South Korea	2011								▨					450		3					
25	Green Sense Farms	Portage, Indiana	US																					
26	Green Spirit Farm											▨												

In section 2.5 of this chapter, the issue of the semantic incongruence in the world of vertical farming has been touched upon. The previous discussion was mainly around the differentiation that should be made between the meaning of Vertical Farms and **Vertical Farming (VF).** Furthermore, the concept of Plant Factories (PF) was also briefly introduced and highlighted in that the term is also directly linked to VF. Beyond these terms, there are a number of other concepts that are directly (or closely) related to VF. *Vertical agriculture* is another common term to describe VF (Molin and Martin 2018a). In 2016, Higgins described that in North America the "vertical farming industry [is] known as plant factories (PFALs) in Japan and as city farms in Europe, is best described as nascent" (Higgins 2016). What Higgins meant by PFAL was a similar concept known as *Plant Factories with Artificial Lighting*. Another recurrent characteristic terminology found in literature that is highly linked to VF is "C*ontrolled Environment Agriculture*" CEA (Despommier 2014; Benis et al. 2017b). The concept of CEA is linked to high reliance and high-end technology, this characteristic also applies in occasions to some forms of vertical farms. However, CEA is not necessarily a synonym of VF. Further terminology is found in a number of publications, such as "*High Density Vertical Growing* (HDVG) [which] can be considered a form of *Controlled Environment Agriculture* (CEA) that aims to allow people to grow food where they live, using fewer resources to produce a higher output" (Frediani 2011). Frediani describes this agriculture as sustainable urban agriculture.

Several authors, often refer to vertical farms with the term Plant Factories (PF), which was briefly mentioned in the previous section. Well-known researchers such as Kozai, have mainly labelled their research as PF.(Kozai et al. 2016b). Similarly, two more published definitions can be found in the relevant literature, directly linked to PF are the *Plant Factories with Artificial Lighting* (PFALs) (Kozai 2014; Mitchell and Sheibani 2015) and the *Plant Production System with Artificial Lighting* (PPALs) (Wang et al. 2016). Based on the mentioned references, it is clear that PF, PFALs and PPALs tend to be directly related to high density food production. Similarly, there is another published concept related to all the above mentioned: *High Density Vertical Growing* (HDVG) (Frediani 2011).

Focused on the influence of the built environment and the interaction between buildings and plants and VF, this investigation also looked into published work related to *Building Integrated Agriculture* (BIA). This is described as "the application of high-performance greenhouse farming methods adapted for use on top […] includes soilless culture methods, such as hydroponic cultivation, a technology that does not use any land" (Benis et al. 2017b). Although, the definition above described BIA as a variation of greenhouse, it can also be found in other structures different to greenhouses (Benis et al. 2017a). Depending on the context, BIA can also overlap with the previously mentioned CEA, and there is a particular publication that describes their research area as *Building Integrated Controlled Environment Farm* (BICEF) (Shamshiri et al. 2018). Furthermore, interesting research presented by a feasibility study report, for a design of a vertical farms in Charleston, highlighted the importance of distinguishing the variation the concepts: *Urban Farming, Sky Farming and Vertical Farming* (ClemsonUniversity Institute of Applied Ecology 2011).

These latter three terms encourage this discussion to attempt to 'untangle' all these concepts that are so closely intertwined. All the information found in these areas have a great potential to enrich the further development of vertical farms, and therefore making them more efficient, sustainable and replicable. It could be argued that there are five important characteristics that influence the shape and nature of the above mentioned **alternative agricultural methods,** these five characteristics can help to classify the different agricultural approaches are:

1. SIZE
2. DENSITY
3. CONTROLS
4. LAYOUT
5. BUILDING TYPE/FORM

Based on the discussion of relevant literature presented above, it can be concluded that the two main factors defining whether any of the previously mentioned relevant agricultural practices (i.e. PPALs, BIA, CEA, etc) could also be classified as vertical farms, are: 1) LAYOUT and 2) BUILDING TYPE/FORM.

VF is about maximizing the available space (and resources), as its name suggests this should be achieved by utilising the space available vertically, therefore even though there can be small vertical farms (SIZE will not determine whether it is a vertical farm or not). In terms of DENSITY, this could be a relevant factor for this classification depending on the point of view. For instance, on one hand the parameter of DENSITY would be the relevant parameters to define the vertical farming method, as long as the crop would be more 'densely-spaced' if considering the amount of product per square meter area. However, if it is a small vertical farm, then it might be argued that DENSITY does not describe a particular case. Finally, the parameters named as CONTROLS are related to the type of technology used to run the vertical farm. This is not considered a relevant parameter to classify a VF, because although most vertical farms would be closer related to high technological systems, some of them would also be a lot simpler and not so highly reliant on technology, complex racking mechanism, etc.

The classification of related concepts to vertical farming are interrelated in the subject matter of study as observed in Figure 14.

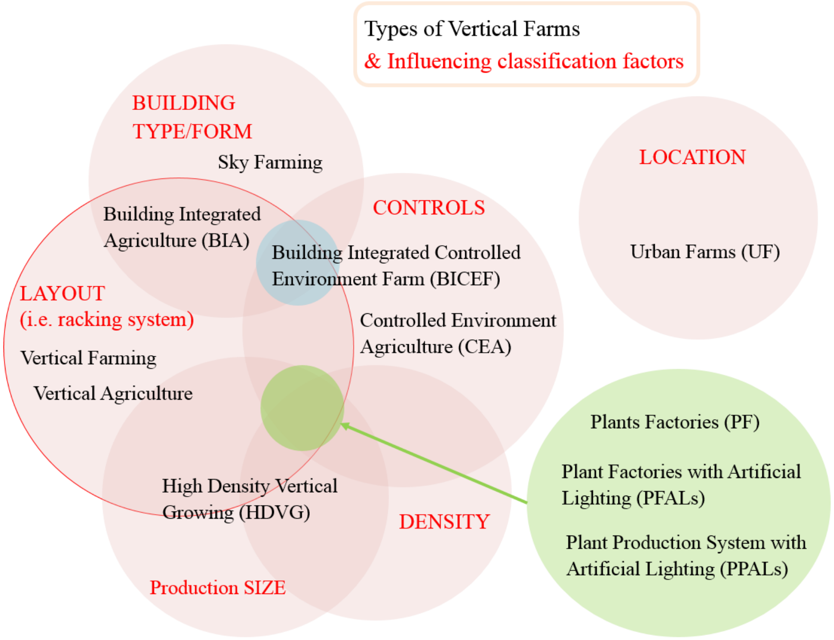


Figure 13. Vertical farming correlation of concepts.

2.9 Latest Development on Vertical Farming

Despite of the significant development on commercial vertical farms (Yang 2014; Sarkar and Majumder 2015; Kozai et al. 2016b; Shamshiri et al. 2018), there is an evident gap in academic documentation of current advances on VF. Most academic journal papers support common premises stressing the need to encourage further development of vertical farms. Various publications agree that some of the main reasons to push this concept further are: the lack of land availability, food scarcity and population growth (Banerjee and Adenaeuer 2014b; Garg and Balodi 2014; Al-Chalabi 2015; Sarkar and Majumder 2015).

It is frequently stated that the main drivers for the evolution of agricultural research are: 1) Fast growth in science and 2) Technological knowledge (Banerjee and Adenaeuer 2014b; Garg and Balodi 2014). The global urbanisation rate is also playing a significant part according to literature, it is predicted that 70% of the population will be living in urban centres by the year 2050 (Al-Chalabi 2015). Furthermore, there is a need to restore the environmental imbalance created by farming chemicals (Despommier 2013; Garg and Balodi 2014). Further issues affecting food demand are the changes in food preferences (Banerjee and Adenaeuer 2014b; Garg and Balodi 2014). These changes are arguably the result of the rising per-capita income, particularly in developing countries (Garg and Balodi 2014; Sarkar and Majumder 2015), as well as the increase of purchasing power (Banerjee and Adenaeuer 2014b). However, they are also likely to be affected by occupational changes and extended global linkages (Garg and Balodi 2014). It is predicted that by the year 2050 the world will need 60% more food, while figures currently show that 1.3 billion tons of food is lost or wasted every year (Banerjee and Adenaeuer 2014b). These later issues are particularly worrying since they show that the main problems affecting food scarcity are not just founded on the depletion of natural resources, but on the lack of efficient management of the available food.

A significant advantage of the VF concept is that vertical farms can be located virtually anywhere, inside or outside urban areas. Therefore, by producing food closer to the end-consumer, the amount of food wasted can be significantly reduced, by decreasing transporting time/distance and also by producing just the right amount for the actual needs of specific locations. This will also help to decrease CO_2 emissions originated from food transport. Currently, one of the main challenges faced by VF is the high requirements for expert knowledge in plant science and engineering (Sarkar and Majumder 2015). Additionally, there are a number of practical problems besides the popularly emphasized financial difficulties. Some of the cited challenges are: difficulty to establish an effective and efficient eco-friendly design of vertical farms structures, difficulty to design a well-controlled environment, watering system, monitoring of nutrient solution, selection of ideal crop, etc. (Al-Chalabi 2015; Sarkar and Majumder 2015).

On the other hand, some of the main advantages are: all-year food production, local need-based production (Sarkar and Majumder 2015), reduced transport needs and reduced food waste associated with transportation (Garg and Balodi 2014; Sarkar and Majumder 2015; Kozai et al. 2016a). Furthermore, it has been found that vertical farms have a much higher crop yield, decreased water usage, less disease transmission – less pesticides, pests, deforestation (Garg and Balodi 2014; Sarkar and Majumder 2015). Published research also claims that VF provide a paradigm shift in terms of agricultural behaviour, by encouraging the concept of intensive agriculture instead of extensive. For example, 1 indoor acre is equal to 3 outdoor acres of strawberries according to (Banerjee and Adenaeuer 2014b). Additionally, VF allows the reuse of buildings (Banerjee and Adenaeuer 2014b; Garg and Balodi 2014), encourages coupling of food production (food + fish, i.e. Tilapia) (Banerjee and Adenaeuer 2014b). Depending on the type of vertical farm, most designs do not require heavy agricultural machinery or inorganic fertilisers and it helps to reduce transport pollution (Garg and Balodi 2014). Further potential benefits of integrating vertical farms in cities are: help to create sustainable urban centres, cleaner air in cities and, also depending on the type of vertical farm, if plants are visually available to people (by integrating them in an indoor environment or on the external elements of the building), this can have a positive psychological effect on people. A good example of how this can be achieved with VF can be seen in the article published by Andrews

(2013). The article includes a collection of several pictures of Pasona, an urban vertical farm in Tokyo, which is an example of a retrofitted building converted into a vertical farm that serves also as an office block and canteen. This example of vertical farm was also included in the historic timeline above (in the year 2010) due to being a significantly positive example of this concept.

2.10 Empirical research in the area of vertical farms

A particularly relevant theme in the VF literature is the systems optimisation. Various projects were identified that have been investigating different methods to improve different aspects of vertical farming methods. For instance, Tsitimpeis et al (2016) suggests the use of a rotating 'robotic' shelving mechanisms to improve air circulation between crops growing in a vertical farming setting. This investigation refers to vertical farms as shelving units (or growing trays) used to cultivate plants. That research investigates the automatic rotation of the growing shelves in order to counteract uneven distribution of resources across all plants (light, air, water, etc).

Further relevant research has been published in the area of test-cells development (Tsitsimpelis and Taylor 2014; Cattarin et al. 2016; Tsitsimpelis et al. 2016). Particularly, the work of (Tsitsimpelis et al. 2016) follows the exploration of a mechanical "conveyor-irrigation system for the mechanical movement of plants" in a VF. They have followed this line of research based on the premise that the un-even air and light distribution across the different levels of a VF result in the loss of quality of some of the plants' growth. As a result, they proposed a mechanical system that ensures all the plants getting the same amount of resources. They claim that the evidence found shows how "the mechanical movement of the trays by means of the conveyor system, helped to minimise the impact of temperature and humidity variation across the different trays" (Tsitsimpelis et al. 2016).

The authors (Tsitsimpelis et al. 2016) in their research support the argument that there is an important need to further explore and improve the concept of VF, under the overarching argument of the "optimisation of the food system , in order to deal with forthcoming changes in population and climate” (Tsitsimpelis et al. 2016). Additionally, research on how the technological developments have helped to improve VFs is evident in a number of papers (Kozai et al. 2016b; Kalantari et al. 2017b; Shamshiri et al. 2018), such as the rapid improvement of LED lighting efficiencies (Despommier 2010; Song et al. 2014; Kozai et al. 2016a; Kozai et al. 2016b; Luna-Maldonado et al. 2016; Tsitsimpelis et al. 2016). However, a number of papers in the area agree upon the issue that LED lighting for agriculture still have not found its maturity (Tsitsimpelis et al. 2016; Graamans et al. 2018).

2.11 Chapter Summary

During this literature review, a sense of lack of cohesiveness of past work of the various disciplines was identified. Moreover, the vertical farms that have been built and are active are mostly commercial enterprises, and perhaps this has resulted on data sharing sensitivity. The author of this thesis believes that this has hindered the progress of this alternative agricultural method. Next chapter will focus on the literature review findings related to the area of simulation of vertical farms.

Chapter 3

A Review on Parameters and Simulation of Vertical Farms

"The loss of biodiversity is a silent killer"

(Palmer 2018)

3.1 Chapter Overview

This chapter provides a review of the literature and vertical farm projects focused on the area of simulation. This section of this research identifies potential gaps within the areas of architecture, alternative agriculture and food production in relation to the potential to develop a novel simulation framework that can connect all the overarching parameters necessary to simulate the behaviour of vertical farms.

3.2 Introduction

As observed in the timeline development (Chapter 2), vertical farms' multidisciplinary nature has been highlighted increasingly throughout the years, ever since the initial events in history that have contributed to its development. This multidisciplinarity has been acknowledged also by different authors (Despommier 2010; Kozai et al. 2016a; Benis and Ferrão 2018; Kozai 2018; Ryymin et al. 2020). Furthermore, a common denominator amongst several of the publications was the issue around financial viability of this alternative agricultural practice (Despommier 2010; Banerjee and Adenaeuer 2014a; DLR 2015; Shao et al. 2016; Hughes 2018). Similarly, authors in this area also discuss the need to improve significant issues such as efficient design, scalability, replicability and environmental sustainability of vertical farms (Almeer et al. 2016; Tsitsimpelis et al. 2016; Benis and Ferrão 2018; Hughes 2018; Tablada et al. 2020)

This has presented the need of addressing one of the key questions of this research:

Can there be a platform or framework to bring all these elements and disciplines together?

Objective 2 of this thesis aims to propose a solution to this gap.

From the analysis conducted in Chapter 2, it became clear that solving these questions required a review of the simulation parameters found in the literature in order to identify the gap(s) in knowledge, which is not accessible only by analysing the examples of operational vertical farms due to constraints related with availability of commercially sensible information, time and resources of this research and the lack of coherence and cohesion of the concepts in this field. There are two main types of case studies found with regards to vertical farms: operational vertical farms and simulated vertical farms. The first type consists of physical installations of vertical farms usually in commercial sectors which are operative and already function in a business model; whilst the second consist of computations made by a software using certain parameters to assess the efficiency of the virtual vertical farm. The literature review of the previous chapter focused on operational vertical farms, whilst this chapter focuses on the review of the simulations and parameters requirements of vertical farms.

During the development of this research, it was found that the data reported from vertical farm case studies can generally be linked to two mainstream sources: Commercial developments (Jans-Singh et al. 2019) and Academic research (Graamans et al. 2018). Therefore, the initial objective was to identify some of the main vertical farming stakeholders across the world for both: operational (as described in Chapter 2) and simulated vertical farms, in order to obtain more detailed information about their methods and characteristics. Added to the information found during the literature review, a significant level of stakeholder engagement took place, aimed to identify potential clues that could help to find possible solutions to the issue of integrating a multidisciplinary set of technologies in areas such as building physics, architecture, plant biology, lighting and ventilation for agriculture, moisture control, energy specialist, urban agriculture, etc, which are required to achieve a truly holistic vertical farm integration in the built environment (Franchini 2016; Basnet and Bang 2018; Bustami et al. 2018).

3.3 Systematic Literature Review

Simulation of vertical farms falls within the remit of the two initially established research boundaries mentioned in Chapter 2: "Architecture and Urbanism" and "Urban Architecture and Food Production" (see Figure 10). The outcomes of the literature review conducted using the systematic methodology described in Chapter 2 (section 2.3), supported the topic that was also highlighted by Shao et al. (2016): There is only a small number of examples of simulations of vertical farms developed to date.

Similarly, the influence of the host building on the behaviour of vertical farms has been largely under-reported. These two important gaps, identified from an early stage of this review, became some of the initial guiding points in this PhD journey.

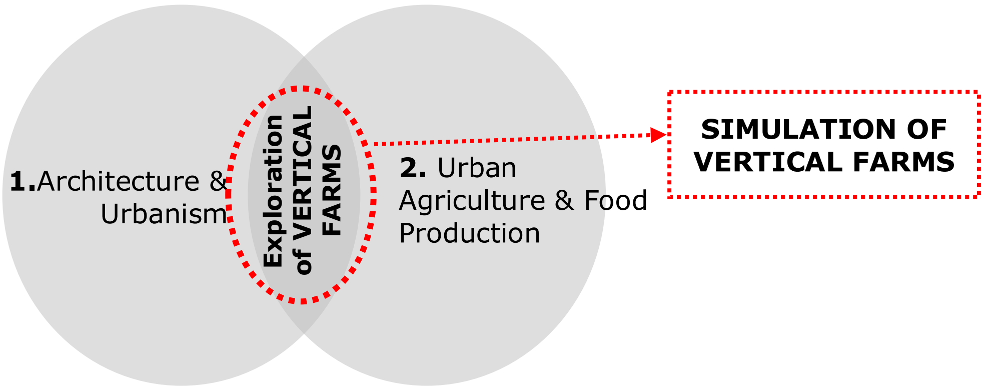


Figure 14. Research boundaries established, following the overlapping of KEY Fields and identified research gaps.

The most relevant research publications related to initial attempts to simulate vertical farms began to emerge as recently as 2015, with the work of Benis et al (2015, 2017, 2018), closely followed by Shao et al (2016), Graamans et al (2017, 2018, 2020), Ward et al (2018) and Jans-Singh et al (2019). Nevertheless, there is still the matter of incongruence amongst the different definitions of vertical farms and related concepts. These simulation models only seem to skim the surface of the issues discussed in this review due to the broad range of concepts that can be linked to vertical farming. For example, the work undertaken by Benis et al (2015) is focused on Building Integrated Agriculture (BIA). In their research, vertical farming is only a fraction of the investigation focus. They also trialled simulated scenarios with greenhouses and roof-top agriculture. On a parallel route, the simulation work undertaken by Shao et al (2016) focused on the economics of vertical farms, whilst Graamans et al (2017, 2018, 2020) priorities were based on comparative scenarios and simulation approaches between Greenhouses and Plant Factories (PFs). Building Integrated Agriculture (BIA) and Plant Factories (PFs) are concepts closely related to vertical farms and will be further explored in the next chapter.

Graamans et al (2020), in this publication, once again the authors further reiterated the significant gap that exist in the area of simulation of vertical farms due to the infancy of this research topic, as well as the urgent need to further develop it. This argument is echoed by Ward et al (2018), Jans-Singh et al. (2019) and Khalil and Wahhab (2020). The above findings have been used to establish and further support the relevance of the overarching research boundary of this doctoral thesis, i.e. simulation of vertical farms (see Figure 10).

Table 7 provides a summary of some of the most relevant authors that have published research work somehow relate to the simulation aspect of vertical farms. Some of these researchers were directly contacted as part of the stakeholder engagement.

Table 7. Academic researchers with significant published work related to vertical farming projects (simulations)

	Author(S)	Year published	Software Usef	Country	City	Description	
1	Graams, et al	2017, 2018	MATLAB, KASPRO+DesignBuilder	Netherlands	Delf	Significantly focused on plant biology, significant lack of evidence on the consideration of the impact of the building fabric.	Contacted and response received
2	Benis, et al	2015, 2017, 2018	Rhinoceros, Grasshopper, Diva, EnergyPlus	USA and Portugal		Focused on BIA (Building Integrated Agriculture), i.e. not much detial on VF specificatly. More focused on details of buildings layouts, less focused on plant biology. All hypothetical work	Contacted and response received
3	Khalil + Wahhab	2020	ENVI-Met	Iraq	Baghdad	Rough attempt to assess the impact of vertical farms at a community scale (not building detailed)- more focused on urban planning than the impact of building materials on plants' growth. Not cosideration of plant behaviour ether.	
4	Ward, et al	2018	Investigated: EnergyPlus, TRNSYS and IES-VE (But deemed them inadequate for VF due to inflexibility) - Therefore used their own mathematical model based on	USA	Delf	Significantly focused on plant biology, significant lack of evidence on the consideration of the impact of the buolding fabric.	
5	Jans-Singh	2019	Mathematical models and monitoring of a case study	UK	London	Scientific models for plant growth are largely empirical and developed for certain types of commercial plants, hence this author claims it is not possible to rely on models alone. Therefore, their work is based on a case study monitoring both qualitative and quantitative data in an existing hydroponic farm.	

Another, very recent, publication (March 2021) highlighted the "need for sustainable farming, the [important] role of precision technology in modern farming and the demand for automation and decision support" (van Mourik et al. 2021). This latter publication provides further and more recent evidence that despite the significant advances that have occurred during the last 5 years, vertical farming remains an alternative agricultural method significantly underdeveloped, despite of its potential.

3.4 Latest developments on simulation of vertical farms

The last couple of years witnessed a great increase in the number of academic research works published in the area of urban agriculture, particularly in VF (Kozai 2013b; Kalantari et al. 2017b; Kalantari et al. 2017a; Shamshiri et al. 2018) .

As previously mentioned, this field is significantly multifaceted (Viljoen et al. 2005; Mitchell and Sheibani 2015; Tablada et al. 2020), where several factors play an important part on the overall performance and outcomes. In-depth research is required in areas related to biology, chemistry, physics, and more that are significant to the efficient implementation of this practice. Just to provide some specific examples:

1. Plant biology and the behaviour of plants: Ward et al (2018) describes an important aspect of vertical farms, the "physical process governing heat and mass transfer between plants and their environment … plant transpiration has been a consistent topic of research over the past 40 years" (Ward et al. 2018, p. 258). Plant transpiration plays an important part on the investigation of plant growth (Graamans et al. 2017). Large part of the above-mentioned research is related to the behaviour of plants due to the significant influence of greenhouses. There has been significant research focused on greenhouses, to the point that a photosynthesis model was first incorporated into a greenhouse simulation in the 1990s and

led to the development of a steady-state simulation tool for tomatoes production (TOMSIM) (Ward R et al. 2018).

2. Despite the significant difference between vertical farms and greenhouses, there is a substantial overlap that have enticed researchers into exploring the potential to use software tools that have been developed in the past for greenhouses, to attempt the simulation of vertical farms (Benis et al. 2017b; Graamans et al. 2018). Benis et al (2017) used it in the context Building Integrated Agriculture (BIA) and Graamans et al (2018) in the context of Plant Factories (PF). There is yet a gap in the specific focus of this investigation under the label of vertical farms.
3. Shao et al (2016) focused their simulation on the economic feasibility analysis using VFar (Shao et al. 2016), making use of excel to include all the necessary mathematical equations that affect the economics of a vertical farm. This model takes under consideration the impact of the building fabric. However, it seems to be modelled around large-scale vertical farms.

Relevant publications highlighted the importance of analysing and calculating the 'energetic behaviour' of crops in order to achieve better vertical farming produce (Benis et al. 2015; Graamans et al. 2017). This brings into consideration a whole new field into this research endeavour: the importance of the biological behaviour of plants in terms of energy saving in the design of vertical farms. How can this behaviour potentially work for or against vertical farms' behaviour? Could the understanding of this biological behaviour help this research find better and more efficient ways to design VF practices? Can we save precious energy by extrapolating this knowledge into a larger scale? A number of modelling methods have been developed in some of the areas that are relevant to vertical farming, for example mathematical models have been used, implementing the Penman-Monteith to determine evapotranspiration of crops (Benis et al. 2017b; Waldron 2018), physics (Orsini et al. 2013) and biochemical models (Soderlund and Newman 2015; Benke and Tomkins 2017) have been investigated largely informing several sectors of plant growth and food production, including greenhouses. Therefore, this concept can potentially help towards modelling the improvement of air-quality of indoor plants, as a result, plants grow faster and healthier if provided with the right balance.

As described by Finkelstein et al. (2005) computer simulations can help test conceptual models that can then be transferred into physical applications, or the 'real world'. Also minimizing the financial risk of 'real world' investments. Having the alternative to simulate a complex environment (i.e. vertical farms) is "useful because they are ubiquitous and expedient in environments with otherwise limited resources" (Finkelstein et al. 2005, p.7). Similarly, Ward et al (2018) also highlight the benefits of dynamic computer modelling, explaining that some of the earliest simulations were developed in the 1970s and 1980s aiming to serve the purpose of offering significant insights to certain problems recreated in the virtual world. This dynamic simulation approach has proven useful for the greenhouse environment, with significant influence on crop yield. "Simulation is potentially a useful tool for optimising growth conditions to maximise the potential profit" (Ward R et al. 2018, p. 268).

Within this context, a recent publication by Van Mourik et al. (2021) describes the complexities that usually take place within farming systems and therefore the value of having a software tool that is robust and flexible enough to allow to get closer to simulate realistic scenarios. In their publication, the authors outline how farming systems are involved with the interconnectivity of many complex components. "These components are subject to the influence of multiple inputs, some of which are controlled, while others are not. A systems model creates structure by describing the components as process variables and by describing their dynamic responses to changes in input. […] a predictive-systems model can be designed to improve input scheduling in scenario studies, in which the insight obtained into the system's input response contributes to the development of practical management guidelines." (van Mourik et al. 2021). This quote is particularly relevant for the task at hand: Objective 2 of this research is to develop and propose a simulation framework, which can potentially align with the description above, aiming to bring together all the relevant elements of vertical farms that interact with eachother.

Aiming to get closer to a solution, which considers as many of the above mentioned "interconnectivity" of the various components of [vertical] farming systems.

Further authors also discuss the potential of simulation development and its current progress, Avgoustaki et al (2020) discuss in their publication the importance of build on existing work (i.e. current simulations attempts) to be able to move forward in this field. "[An] important aspect of further research is the computer simulation models and adaptive analysis software tools already used. More research and development groups need to focus on the extension of these programs, and modify the already existing ones for this specific purpose" (Avgoustaki and Xydis 2020).

It is well-known that knowledge-transfer holds significant potential towards the advancement of many research areas, this is particularly true in fields that are in their infancy, which it is the case of VF. Graamans et al. (2018) tap into the potential learning that can be captured from understanding the behaviour of greenhouses and the knowledge that can be transferred to analyse vertical farms. In contrast to vertical farms, greenhouses represent an agricultural method that has been around for years and it is well established. Their investigation (Graamans et al. 2018) explores how the knowledge and skills used to manage and model greenhouses, provide an important insight into how to potentially improve the design of vertical farms (Graamans et al. 2018). In this particular paper, Graamans et al. attempted to overcome the issue around the lack of suitable software to simulate vertical farms by using two separate software tools: KASPRO, which is a common software used to calculate the behaviour of greenhouses, and DesignBuilder as the software used to attempt to recreate the influence of the building hosting their conceptual VF. Despite the good premise of this investigation, the lack of clarity on their method and the resources used for this simulation attempt, suggested that there are significant gaps yet to be filled in order to be able to undertake this kind of simulation attempts in the right way. For example, the simulation they suggest requires detailed building materials' properties, but the building details are only touched on superficially and a number of unexplained assumptions are made along the process in order to explore this pathway. This publication also highlighted that there are a lot of gaps and development requirements in the area of VF simulation.

Graamans et al (2018) on the other hand suggested a comparative understanding between plants factories (which are commonly referred to as vertical farms) and greenhouses. His investigation uses simulation methods to understand and compare the efficiency of both agricultural practices. Benis et al (2017) provides an interesting comparison between all types of Building Integrated Agriculture (BIA) explaining some attempts to simulate comparative urban agricultural methods. The area of simulation methods will be discussed in more detail in the next section.

3.5 Available software tools for vertical farming

In terms of software tools available for vertical farms, there are two possible ways to classify this topic: 1) the monitoring software tools to run and manage vertical farming systems that require high-end technology. 2) Simulation software to predict the behaviour of vertical farms. In the first instance (monitoring software), information regarding the tools used to monitor and manage vertical farms tends to be available only in commercial circles, very little information is published in the academic context. There is not such a thing as open-source material offering transparency or collaboration across the vertical farming community. Unsurprisingly, in commercial circles the vertical farming technology (including software tools) tend to be a rather ‘guarded secret’ for each individual enterprise.

On the other hand, the latter item (simulation software) continues to represent a significant gap in research. There is not a well-recognised method to simulate a vertical farm (Kozai et al. 2016b; Graamans et al. 2018) to aid with the assessment of its efficiency and to suggest optimisation pathways. All optimisation attempts of vertical farming practices have occurred under empirical research methods, not through simulation.

A key potential identified as part of this PhD research is the significant opportunity to learn from the wealth of knowledge that can be extracted from the process followed to analyse and simulate the energy performance of buildings, such as simulation models that are based on energy balance calculations. The development of simulation methods and tools to understand and optimise the "behaviour" of buildings have been undergoing for several decades (Ward R et al. 2018). But these methods have not been tested with the integration of vertical farms. A number of additions must be considered, especially in terms of integrating the characteristics of plants within the built environment, but if the simulations can account for the presence and influence of humans, what can be holding back any plausible attempts to also do it with plants? There are already a number of mathematical models that provide numerical values to the behaviour and predictions of plants, such as the Penman-Monteith equations or the Vanthoor model, mention earlier in this chapter (Allen 2005; Benis et al. 2017a).

Considering the discussion above, it can be noted that there are a number of validated software tools that can help simulate buildings such as TRNSYS, HTB2, EnergyPlus, Ecotect, IES-VE and more. Therefore, it could be argued that a bridge could be found to link these two significant areas of simulation: simulation of buildings, including the interaction and influence of the behaviour of indoor plants/crops. However, Ward et al (2018) claim that these standard simulation models cannot be used for greenhouses and vertical farms due to the complex integration of plants with their environment.

On this note, Graamans et al. (2018) developed a study around the comparison of greenhouses versus plant factories (or vertical farms). In their paper they described the use of a building performance simulation tool (Design Builder) to tackle the building performance aspect of the "equation" and linked the investigation to a software tool used by greenhouses simulations known as KASPRO. In their publication, Graamans et al (2018) stated a number of limitations to their approach, but the authors also highlighted a number of important questions in terms of potential to tap into the knowledge-transfer possibilities of two key areas that have been yet untapped with relation to vertical farming:

1. Research on the behaviour of plants
2. Research on the behaviour of buildings

This doctoral research found that vertical farms will gain significantly from having a software method or FRAMEWORK that will help to develop some initial predictions regarding the efficiency of a planned vertical farm. By doing so, initial rough estimations can be made at an early-stage, highlighting which factors should be considered and potentially re-tweaked to ensure an optimised deployment of a vertical farm, therefore reducing the chances for this vertical farm to underperform. This is especially important due to the high investments that these developments require.

One important characteristic that will allow a software tool to attempt to create a simulation framework for a vertical farm will be: **flexibility**, amongst various other important features. This is due to the previously discussed multidisciplinarity of this field., i.e. a realistic simulation needs to consider the constant interaction between plants and the host building, which should include all the complexities that both of these "worlds" represent.

Bearing in mind the importance around flexibility, as well as affordability, the main software tool scoped to assist the development of a simulation framework for this research project has been HTB2 (Heat Transfer in Buildings) (Lewis and Alexander 1990; Alexander 2008), which is not a commercial software (but a research software), it can be freely downloaded and it is also open-source (which adds the potential flexibility to explore the source code in future studies). It was originally built to recreate the thermal behaviour of buildings. Its engine uses mathematical models and the laws of physics to calculate their internal temperature, predict energy consumption, humidity, amongst various other parameters. This tool has been validated, nonetheless the capabilities of this tool have never been explored to simulate vertical farms.

By developing a novel HTB2-based Framework for the early-stage simulation of vertical farms, this investigation can help to create a methodology to predict and estimate the efficiency of vertical farms, aiding to plan for its optimisation and reduce the risks of deploying an unsustainable vertical farm. Furthermore, due to the open-source nature of this software tool, this framework can offer a measurable method that can help to create an open database for vertical farms across the globe, encouraging research collaboration. By being able to use a common 'language and format', i.e. a standardised framework method and calculations, this will facilitate comparability, replicability and the ability to share with a wider audience. Therefore, the VF community will be able to use sharable information, regarding the efficiency of an existing vertical farm (or planned), in order to create synergy and aim to improve their overall efficiency across the globe.

HTB2 is an in-house developed software tool, initially created at the Welsh School of Architecture by an experienced building physicists and programmer in the 1980s. It has been further developed and validated ever since. HTB2 has been widely used in several projects around the world. The main purpose of this software has been to assist research, not for commercial purposes. This software considers several parameters simultaneously, allowing them to interact and influence each other. including in its calculation how these parameters influence each other. The software is of a modular nature, this will be better explained in the next chapter. Furthermore, the calculations embedded in the source code, also include the thermal mass of the materials (which can be a significantly beneficial parameter in terms of thermal stability for vertical farms, which is usually disregarded in this context – particularly in terms of 'hydroponics', due to the large presence of water in the circulation system, there is a potential to calculate what is the thermal mass benefit resulting from having that water in the building alongside the plants). Furthermore, HTB2 can help to predict the energy consumption (which is one of the biggest obstacles of vertical farms as commercial enterprises, the high cost linked to operational energy due to artificial lighting and ventilation loads). Finally, amongst several other parameters, HTB2 also considers humidity within the simulation. This is particularly significant for the context of plants as the 'users' of the building.

As a result of the above, this research project has been focused on exploring the capabilities of this software tool (HTB2) to recreate the behaviour of vertical farms. Bearing in mind that the main limitations of this software to simulate vertical farms would evolve around potential shortcomings of the characteristics related to the behaviour of plants. Nevertheless, this tool possesses significant potential to make it worth exploring this path. Consequently, helping to create a methodology to potentially predict and share data that will result in the improved efficacy of vertical farming practices.

In conclusion, the flexibility and compartmentalised nature of HTB2 has the potential to fill a number of the gaps found during the literature review of this investigation. These are the main gaps identified, which have the potential to be tackled by the development of this simulation framework:

- Lack of building materials in any of the published simulations of vertical farms and/or any kind of vertical farms. Most published work (if not all) in vertical farming are quite content in assuming that the 'host building' for the crops is just a "well insulated, airtight structure" (Kozai 2016). The only research found that actually made an attempt to provide a bit more detail than that was Grammans (2017), where in his attempt to use design builder he established certain material parameters, but not in too much depth. His research went on, like most of the research projects in this area, into the calculations required to simulate the behaviour of plants. This brings an interesting point: vertical farming analysis has usually been approached from the plants perspective, very rarely from the building perspective. In the thermal behaviour of buildings, the materials of the envelope of the construction is of high importance, therefore it has been surprising that this has been largely ignored.

  HTB2 has the potential to provide answers for this gap in the research of vertical farms, its module BLD, focuses on the analysis of the parameters relevant to the building materials (u-values, etc). This is important for vertical farms because the characteristics of these materials will have an impact on the indoors environment (mainly its temperature and humidity). Consequently, this will have an impact on the ideal conditions maintained for the healthy growth of plants. Moreover, another module known as SRV in HTB2, deals with the calculations related to the services of the building, for example, the ventilation rate, or heating rate to maintain the air quality indoors. Furthermore, this module also deals with moisture control, which is significantly important for vertical farms.

- Need for more available reliable data on temperature, air movement and speed (or ACH) to maintain the air quality of the vertical farm.
- Need for research on the potential of renewable energy used in vertical farms (Tablada et al. 2020) in order to make this practice a more affordable and sustainable one.

3.6 Gaps in the field of vertical farm simulation.

To summarise, as evidenced in previous sections, published literature has shown the low numbers of research projects undertaken in the field of vertical farms compared, for example, to green wall/roofs. This investigation has therefore identified a significant gap in research, as well as a potential suitable path to explore the possible solution/options to fill this gap. The development of a simulation framework for vertical farms has the potential to improve the area of vertical farms.

Therefore, in the process of narrowing down the research scope towards the search for specialised solutions, the next level of boundaries outlined for the continuation of this investigation have been mainly focused on the simulation of characteristics only related to vertical farms (no other alternative agricultural or architectural scenarios) and to scope the capabilities of HTB2 for be the software tool used to develop the framework. This process seems to be the most suitable pathway to bring together the various elements related to vertical farms into one platform.

The focus of Chapters 2 and 3 have been around:

> ***Objective 1: To review the State of the Art of vertical farming, the different methods used in this alternative agricultural practice and establish the most appropriate method(s) to be recreated through the simulation process and data analysis.***

The above issues provided initial clues about some of the more urgent gaps that need to be tackled in order to make this practice more sustainable: early-stage planning and calculations. It is undeniable that vertical farms need to be made more efficient, part of the process of making anything more efficient is through planning. This PhD project aims to investigate and fill some of the gaps towards helping vertical farming field to achieve higher maturity and to become a more viable agricultural practice. Nonetheless, this thesis is targeting to achieve to get knowledge, perhaps one step further, but many other steps are required, in the endeavour of achieving more efficient methods of alternative agricultural methods, striving for food security, a better utilisation of resources and making our cities more sustainable.

Vertical farming can be perceived as a form of 'disruptive innovation' (Colnago et al. 2021), as such the challenges faced by this practice need more work to be developed. The work presented here is an attempt to trial a novel prediction methodology, a framework that aims to optimise vertical farms, by understanding its potential efficiency before it is built. This work has documented the process followed and the files created as a result of this investigation, in order to provide a replicable methodology that can be used for any vertical farm around the world. Ideally, this can potentially be a steppingstone into a sharing platform for vertical farming knowledge.

It is popularly recognised in the vertical farming community that there are significant gaps of knowledge that need to be filled in this area in order to improve it, optimise it and make it a viable agricultural method to be widely practiced, this is an area that is still at its "infancy" (Higgins 2016; Storey et al. 2020; Zimmerman-Loessl et al. 2020). The consensus opinion is that the largest obstacle slowing down the wider implementation of this agricultural method is the high financial requirements (Shao et al. 2016; Hughes 2018; Avgoustaki and Xydis 2020). The initial capital investment and the running cost of vertical farms are widely acknowledged to be high. One of the main culprits of the high running cost of vertical farms is artificial lighting (Higgins 2016; Kozai et al. 2016a).

At present, most vertical farms are not financially viable, one example of this significant issue is Japan. This is a country where there has been significant investment in the development of vertical farms (or plant factories) due to this country's pressures, i.e. scarce land availability and natural resources, linked to the significant impact of natural disasters. These issues triggered the need to speed up research and implementation in the area of alternative food production methods. Despite of its privileged high-technological position and fast-paced development in the area of vertical farming, only 25% of their vertical farms make a (generally small) profit, 25% of them run at a loss (they need to be heavily subsidised by the governments) and 50% of them break even (Kozai et al. 2016b) this statistics has been updated to 50% plant factories that make a profit in the latest edition of the book (Kozai et all 2019). Around the world, there are several examples of vertical farms that managed to overcome the first significant hurdle of finding the initial large capital investment, to then succumb to the hefty running costs. According to Higgins (2016): "In order to be successful in today's vertical farming market, the following equation is most often true:

High plant density + low light crops + short production cycle + niche crop + niche market = success

There is irrefutable evidence that the vertical farm concept is rapidly evolving and the obstacles will perhaps become more manageable in the future.

3.7 Chapter Summary

In summary, vertical farms required a multidisciplinary interaction in order to achieve holistic integration with its host building and the various other interacting elements (Benis and Ferrão 2018), in order to create successful vertical farms, i.e. efficient and sustainable. A framework could standardise the concept and definition of the subject matter of Vertical Farm. Furthermore, the availability of technological tools like software represents an opportunity to advance the state of the art of the Vertical Farms.

Chapter 4
Methodology

"Of all the resources needed to sustain a city, none is more important than food"

(Lim and Liu 2010)

4.1 Chapter Overview

Due to the multifaceted nature required for the research and development in the area of vertical farms (Franchini 2016; Kozai et al. 2016a), various research methods were investigated. The nature of the convergent mixed-methods approach selected for this investigation was suitable due to the number of research techniques that were required to undertake this work. The main strategies used to gather evidence and undertake analysis were:

- Systematic literature review: Establishing the State-of-the-Art of vertical farms and data gathering (i.e. gathering parameters to potentially test the development trials of the simulation methodology).
- Scoping study: Developing a network of contacts in the field of vertical farming. Searching to establish connexions within the various relevant areas impacting this field. The stakeholders identified during this communication and engagement activity was crucial, in order to stay up to date with this fast-paced area of research, as well as to identify relevant case studies and databases.
- Development of analytical and conceptual framework assisted by simulation.
- Real-life (active) case study: The data of this particular case study assisted the testing of the aforementioned framework, which was

developed and tested as part of the original outcomes of this research work. This final part of the investigation allowed the comparison of monitored data vs simulated data for the first time in the vertical farming world, based on the published work available to the date of the delivery of this PhD Thesis.

The investigation process was of similar nature to the mixed-method sequential explanatory study explored by Crestwell et al (2003) and Ivankova et al (2006), where quantitative and qualitative methods were used in conjunction to inform the investigation. Based on the above information, the three key reasons that helped identifying the "convergent" mixed-methods approach as the most appropriate for this research were: 1) The nature of the qualitative data (which was gathered from mixed sources, such as published references, as well as stakeholder engagement); 2) Quantitative data collected (via literature review, simulation development and stakeholder engagement); and finally 3) The active commercial case study (which provide further quantitative data for the comparative studies).

4.2 Introduction

It is a well-known issue that the boundaries between different research strategies are "permeable", as described by Groat & Wang (2013) and in many occasions the aspects of one method can successfully augment the characteristics of the other interacting methods. Furthermore, in the book Architectural Research Methods (Groat and Wang 2013) define research styles as "research strategies" and research methods as "tactics". They developed a classification of seven research strategies or methodologies that are widely used in architectural research: Interpretive-historical, Qualitative, Correlational, Experimental and Quasi-experimental, Simulation and modelling, Logical argumentation and Case study, and Combined strategies. Selecting the latter one - "Combined Strategies" (or Mixed-Methods) will provide this investigation with what Clark & Creswell (2008) eloquently described as "an umbrella to cover the multifaceted procedures of combining, integrating, linking, and employing multi-methods." (Clark and Creswell 2008), which is exactly what this topic requires. Furthermore, Groat and Wang (2013) also described how simulation can be implemented as part of the mixed-methods approach relating the role of simulation as a tool to "augment" research.

Therefore, due to the nature of data (quantitative and qualitative), the complexity of a multidisciplinary new approach and the presence of simulation, indeed a mixed-methods approach was followed. This type of methodology can help to "provide greater depth and/or validity concerning [all the] particular aspect[s] of the study" (Groat and Wang 2013). More specifically, the focus of this thesis is a convergent mixed-methods approach (Creswell 2014), where the relationship between the three parallel methods are compared, to feed into the final overall picture. Henceforth, the inclusion of stakeholder engagement is an important part of the research activities, in order to further obtain granularity on the information that might not be as detailed in the published realm. Furthermore, the information collected during the systematic literature review is also an integral part of the research methods, since along with the scoping study information, the data is gathered to inform the development of the analytical framework for vertical farms. Thereafter, the framework can be tested with a real case study to assess the results. Due to this significant correlation between all stages of the research this is a convergent Mixed Methods research.

In most of the vertical farms analysed, one of the concerns was to develop ways to increase the optimisation of the processes and there was also a lack of integration with renewable sources to achieve sustainability of the model. It is common knowledge in the vertical farming world that this agricultural practice used 90% less water than traditional agriculture (Al-Kodmany 2018; Avgoustaki and Xydis 2020). Furthermore, the potential to use rainwater harvesting for this practice is significant and it should be further explored and implemented (Orsini et al. 2013; Safikhani et al. 2014). Orsini et al (2013) in their paper they present the exploration of various methods used to develop urban agriculture in developing nations, were the drivers to reduce the amount of use and waste of resources are significantly higher. They suggest urban farmers to integrate 200-250 litres water tank on the roofs, to harvest the rain water to use to grow their urban crops. “These systems are particularly useful for urban producers since they do not require high starting capital” (Orsini et al. 2013).

Despite of the many benefits of vertical farms, it is undeniable that there is an imperative need to make them more resource efficient, in order to allow them to thrive. One of the main culprits of resource expenditure in vertical farms is the energy required for lighting, when the farm does not have access to natural light. Nevertheless, due to the nature of the different needs required to provide plants with their specific ideal environment to thrive, places significant amount of resources to ensure that the plants can have the right level of humidity, ventilation, temperature, nutrition, CO2 levels, etc. The controls to manage and balance all the necessary parameters can tend to be also another high consumer of resources and therefore financially demanding. As a result, this investigation places a focus on the viability of alternative sustainability characteristics that can potentially be coupled to vertical farms in order to make them also more environmentally friendly in terms of resources efficiency and usage.

In summary, vertical farms required a multidisciplinary interaction and the uses of different types of methodologies in order to achieve holistic integration with its host building and the various other interacting elements, and to create successful vertical farms, i.e., efficient and sustainable. Until now, little of the research undertaken in the vertical farming world is shared with the academic community, VF tends to evolve behind closed doors. Therefore, it is not surprising that “the vertical farming practice is still in its infancy” (Jans-Singh et al. 2019; Storey et al. 2020; Zimmerman-Loessl et al. 2020). This lack of collaboration and transparency in research reduces the opportunities to work at a multi-disciplinary level, in order to allow this field to achieve its maturity.

4.3 Methodology

The diagram provided in Figure 15 depicts a summary of the various elements that are included in the methodology of this research project. As previously seen in chapter 2 and 3, vertical farms are a multidisciplinary practice which requires multifaceted analysis. Different research methods will allow different data to be gathered, therefore the most appropriate approach must be chosen. For instance, Jick (1979) described that "various notions share the conception that qualitative and quantitative methods should be viewed as complementary rather than as rival camps" (Jick 1979). The mixed-methods approach tailored to this research project consists of three stages:

1. A systematic review of the literature conducted to identify the suitable candidates of vertical farm case studies and simulations which are relevant for the present research project.
2. The subsequent stage consisted of filtering the key operational projects and simulations identified for further analysis and investigation to determine which are selected to attempt contact.
3. In the final stage, the key projects are filtered and contacted to attempt further engagement activities and conduct further studies or collaborations whilst creating a list of the current state of the operational and simulated vertical farms.

Therefore, the established "tactic", i.e., Research Method, comprising the characteristics described above and providing a robust three-fold combined methodology approach, is followed throughout in this thesis as can be seen in Figure 15. The details of the structure of this research therefore follows the three main stages:

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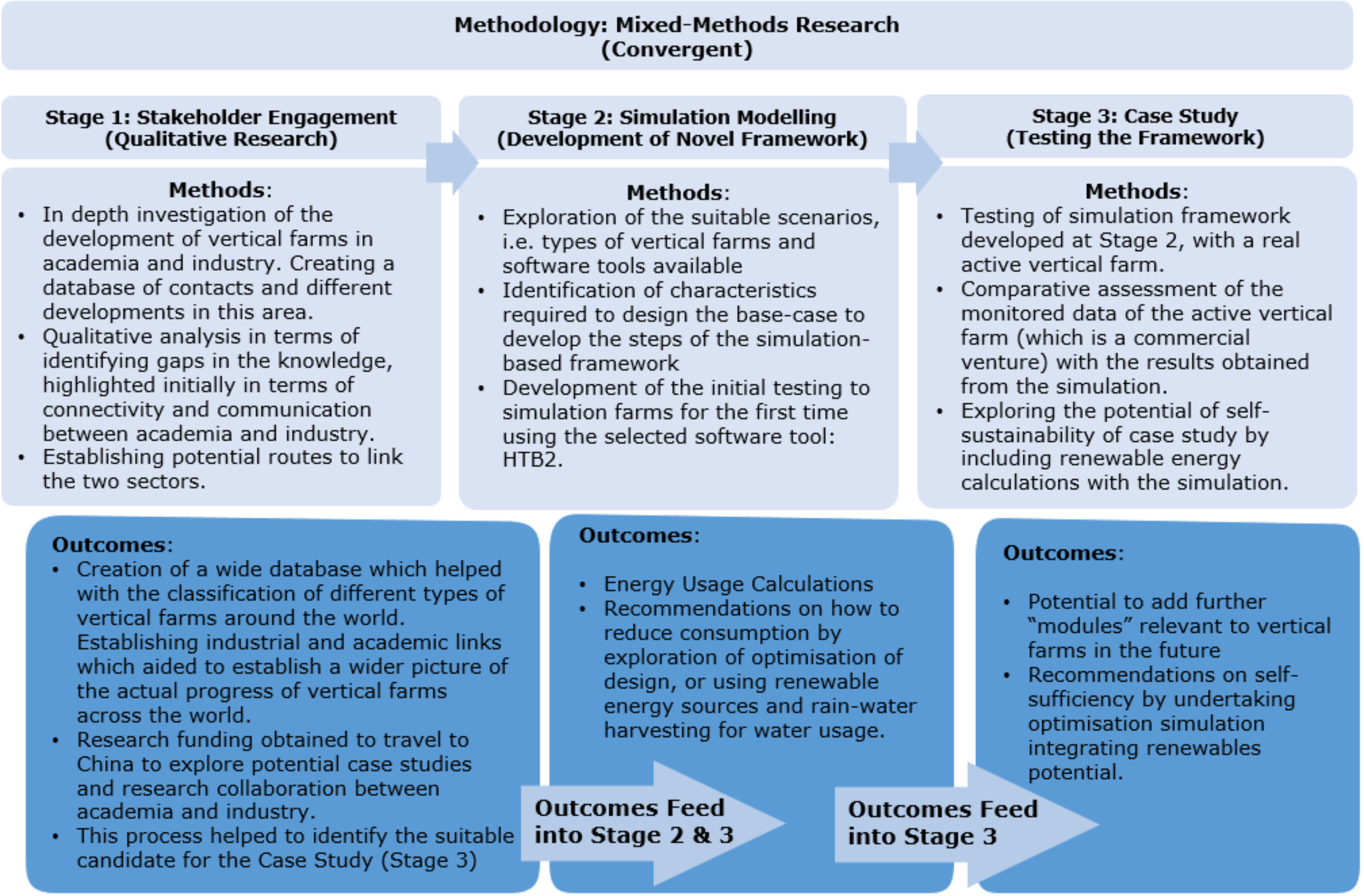


Methodology: Mixed-Methods Research (Convergent)

Stage 1: Stakeholder Engagement (Qualitative Research)

Methods:
- In depth investigation of the development of vertical farms in academia and industry. Creating a database of contacts and different developments in this area.
- Qualitative analysis in terms of identifying gaps in the knowledge, highlighted initially in terms of connectivity and communication between academia and industry.
- Establishing potential routes to link the two sectors.

Outcomes:
- Creation of a wide database which helped with the classification of different types of vertical farms around the world. Establishing industrial and academic links which aided to establish a wider picture of the actual progress of vertical farms across the world.
- Research funding obtained to travel to China to explore potential case studies and research collaboration between academia and industry.
- This process helped to identify the suitable candidate for the Case Study (Stage 3)

Stage 2: Simulation Modelling (Development of Novel Framework)

Methods:
- Exploration of the suitable scenarios, i.e. types of vertical farms and software tools available
- Identification of characteristics required to design the base-case to develop the steps of the simulation-based framework
- Development of the initial testing to simulation farms for the first time using the selected software tool: HTB2.

Outcomes:
- Energy Usage Calculations
- Recommendations on how to reduce consumption by exploration of optimisation of design, or using renewable energy sources and rain-water harvesting for water usage.

Stage 3: Case Study (Testing the Framework)

Methods:
- Testing of simulation framework developed at Stage 2, with a real active vertical farm.
- Comparative assessment of the monitored data of the active vertical farm (which is a commercial venture) with the results obtained from the simulation.
- Exploring the potential of self-sustainability of case study by including renewable energy calculations with the simulation.

Outcomes:
- Potential to add further "modules" relevant to vertical farms in the future
- Recommendations on self-sufficiency by undertaking optimisation simulation integrating renewables potential.

Figure 15. Details of the research methodology

4.3.1 Stage 1 – State of the Art of vertical farms and Stakeholder engagement: Qualitative Research

Following the systematic literature review described in the previous chapter, a scoping study was conducted engaging with stakeholders from academia and industry in order to gather further updated information in the field of vertical farming. Furthermore, this scoping study was also aimed to find real-life case studies to develop simulation based on their characteristic. Chapter 5 provides further details of the scoping study and the site visits which thereafter led to finding the commercial collaborator to undertake the case study at a later stage

Scoping studies

The overarching topic of the research in question: Vertical Farms, involves a number of layers of expertise and knowledge, making this topic a broad subject. According to Daudt et al. (2013), scoping studies are "to map rapidly the key concepts underpinning a research area and the main sources and types of evidence available, and can be undertaken as standalone projects in their own right, specially where an area is complex or has not been reviewed comprehensively before". Indeed, the scoping study was conducted as a complement of the literature review which was comprehensive enough to understand that some of the methods and practices of the industry are not readily available in peer-reviewed publications. This is in part due to the infancy of the vertical farming industry (Higgins 2016; Benis et al. 2017b; Graamans et al. 2018; Khalil and Wahhab 2020), but also because of commercial sensitivity of the business-oriented vertical farms.

Another issue that contributed choosing the scoping study was the multidisciplinary nature of vertical farms. Although several authors address vertical farming multidisciplinary nature (Despommier 2010; Gillott et al. 2014; Al-Chalabi 2015; Sarkar and Majumder 2015; Shao et al. 2016; Al-Kodmany 2018), the literature review conducted showed that not enough collaboration and information transfer has happened across the vertical farming community, making it difficult to collate and agree in the best practices for the development of this agricultural method. One of the ways to aid with this was using the scoping study to map the current panorama of vertical farms globally, selecting primarily the vertical farms or plant factories that adapt better to the aims of this thesis. At this point, the literature review conducted aided in selecting the projects that were still active but also that fell into the category of vertical farm or plant factory, as understood for the aims of this thesis. This is due to the issue observed while conducting the literature review chapter, i.e., the lack of standardization in the definition of vertical farms, according to which the many terms used in the community to refer to the same or similar concepts, affect the generalisability of the methods and practice used. Following the filtering process, the engagement with stakeholders proceeded, in order to determine whether there is possibility to exchange data and knowledge about the processes used in the vertical farm.

Engagement

Based on the information found on the literature review, the next step was to engage with vertical farming key stakeholders and academics that were identified as relevant for this investigation. Engagement in this context was conducted by contacting the principal authors of peer reviewed publications to gather information about the insights of their work and try to fill the gaps identified across the literature review in terms of, for example, the parameters used for simulation of vertical farms. In addition, having filtered the most suitable active vertical farms, exploratory contacts were undertaken with stakeholders and operative personnel to investigate the possibility of conducting further studies such as field research and interviews. This engagement was valuable not only for the filtering of the candidates to select the field study (having successfully selected the vertical farm that served for the case study through this process), but also offered important further information. Whilst a number of vertical farms could not offer to share data, these interactions and in some cases detail communication, presented the researcher with valuable insights regarding the nature of the commercial sensitivity around the development of different vertical farms.

To present a holistic picture of the State-of-the-Art of vertical farms, this investigation found the guidance provided by Groat & Wang (2013) suitable for this context. As can be seen their book on Architectural Research Methods, the "additional attributes of qualitative research" (Groat and Wang 2013) are extremely valuable to a research project of this nature, where the literature review revealed a significant amount of published work related to vertical farming, but also a lack of cohesion in terms of the language used internationally.

In order to set a relevant boundary for this type of qualitative research, it was decided that comparative information and learnings of the vertical farming field at a national and international level were significant. Further details on the selection of the case studies can be found in chapter 5. Based on the scoping assessment, case studies were under consideration across two countries: UK and China. China was selected as a potential option to create comparative studies at an international level. Liu and Teng (2017) described China as one of the countries with the greatest concentration and growth of plant factories, i.e. vertical farms. This was therefore undertaken in parallel with the engagement in the United Kingdom. Key organisations were selected in both countries for further investigation and to potentially undertake site visits and initiate research collaboration. This was with the purpose to find collaborative research, monitoring and calculations collaborators. Some of these key stakeholders or operational vertical farms could be used at the next stage of this research work, as case studies for the development of the simulation framework developed as part of this PhD investigation.

The reason to include some form of qualitative data gathering as part of the analysis (during the stakeholder engagement) are mainly these two:

- According to Hennink et al (2010) "qualitative research is useful for exploring new topics or understanding complex issues" (Hennink et al. 2010).Vertical farming fits this description rather well. In their book (Hennink et al. 2010) highlighted ten reasons to undertake qualitative research. Amongst these ten reasons there were some that resonated more in relation to the applicability in the investigation of this topic: “Qualitative research is conducted to provide depth, detail, nuance and context to issues” in topics that might be too “complex to be easily disentangled by quantitative research.” (Hennink et al. 2010).

- The previous description links the above statement to vertical farms, Kozai et al (2016a) represent succinctly in their book the large number of different research areas that concern vertical farming, as can be observed in Figure 16.

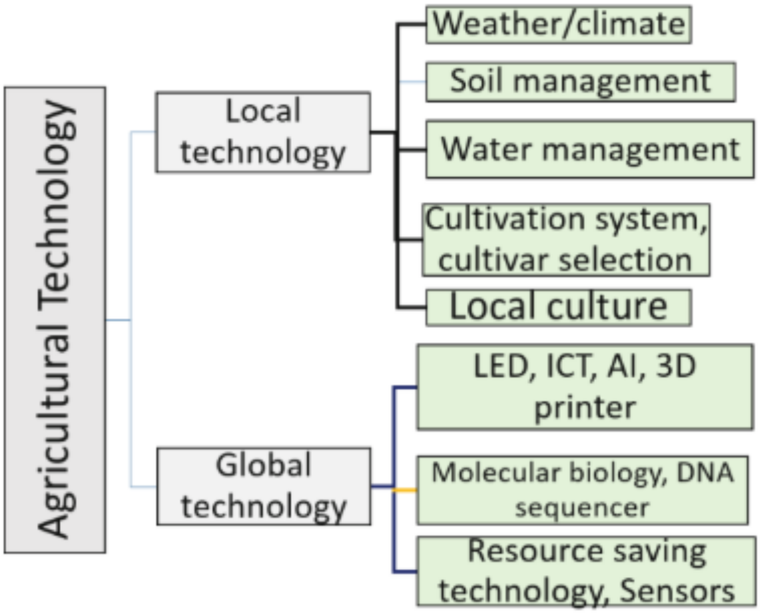


Figure 16. Diagram of Agricultural Technology
from Kozai et al. (2016a)

The Policy Brief “High-Tech Plant Factories: Challenges And Way Forward” (Liu and Teng 2017) published in collaboration by two leading universities from Singapore, highlighted information about some of the most prominent researchers and experts in the area of vertical farming from various countries around the globe. China was highlighted as one of these countries, where the “Ministry of Science and Technology brings together researchers, farmers and companies to develop breakthroughs in intelligent plant factory production technology” (Liu and Teng 2017).

Accordingly, further engagement was undertaken with projects located in China, in order to explore possible collaborations and obtain information regarding the parameters and characteristic used for operational and simulated vertical farms. The initial step consisted of contacting stakeholders of the following VF in academic and commercial contexts, in order to identify its representative and exploring the possibility of further engagement activities and additional funded possibilities.

Four out of five key stakeholders of vertical farms in the UK were interested either in collaboration, sharing information and/or allowed site visits. In contrast, one out of five contacts made in China responded to the request. The respondent in China, eventually became the international academic partner that offered to host the author of this thesis during her PhD placement in Shanghai. One stakeholder in the UK responded to notify that no longer operates as a vertical farm. Finally, one stakeholder based in London, responded to express his interest in collaboration and data sharing.

Furthermore, information was also discussed with stakeholders, such as potential sustainability scenarios to co-locate vertical farms, i.e., Anaerobic Digestion plant (AD plant). One of the face-to-face discussions held with an academic collaborator was to gauge the viability of a case study integrated with an AD plant. The meeting took place with an expert on AD based in Cardiff. Further examples are also related to the exploration of renewable energy integration, amongst several other important and relevant investigations.

4.3.2 Stage 2 – Development of an analytical framework for vertical farms (assisted by simulation modelling)

A common theme across the international vertical farming community is the variation of vertical farms. There is not one standard concept of method to guide on the best practice of this alternative agricultural method. As presented in the literature review chapter, this is a field teeming with discrepancies and a variety of concepts that are related to vertical farms, but not necessarily the same. In addition, there is significant difficulty in finding and accessing information. This is likely to be due to the multidisciplinary and multifaceted nature of vertical farms (Shao et al. 2016; Tablada et al. 2020). As a result, an analysis framework was developed and explored in order to tackle the above issues. To develop the framework, the need of an assisting software tool was identified.

Therefore, various software were investigated, such as DesignBuilder, Sketchup/Virvil plugin, HTB2, among others.

In order to select the most appropriate tool, a set of criteria was established depending on the principles of flexibility, accessibility and convenience. The flexibility requirement alluded to the fact that the selected tool should have the possibility to input different types of data, including environmental data of the building and plant behaviour. The accessibility requirement referred to the need for the selected tool to be open source, which will consequently allow for future modifications. This will facilitate the necessary ‘add-ons’ or ‘bolt-ons’ that will help to further this simulation methodology. This feature is paramount in such a multi-faceted field and still considered at its infancy. Furthermore, a free and open source software tool will be more in line with the reality of current vertical farms, where most of them currently struggle to achieve a positive financial balance (Kozai et al. 2016b), they rarely can afford an added financial burden.

Finally, the convenience requirement alluded to the fact that the author of this thesis had pre-existing knowledge in some of the tools that are being explored as potential candidates for this task. Due to the number of probable tools that could be assessed as part of this study, it was a significant advantage to have such pre-existing background knowledge. The task at hand at this early stage was to assess the flexibility of the software tools, not just to develop an original framework to simulate vertical farm scenarios, but also to allow future potential modifications of the software.

Finally, the most appropriate tool was selected based on the identified needs highlighted in the outcomes of the literature review, the state of the art and the scoping study. The chosen software: HTB2 (Heat Transfer in Buildings). Details and reasoning behind the full selection process can be found in the next chapter. The construction of the framework was originally developed with the aim of building up on information and parameters found in the literature and engagement with vertical farmers, these parameters were summarised in Table 10 (Chapter 5, section 5.5.1.2).

These parameters were used to aid the development of the framework methodology, nevertheless there were significant gaps in the literature and amongst active farms, as it can be noted by the number of blank cells both in Table 10 (Chapter 5, section 5.5.1.2), as well as in Table 6 (Chapter 2, section 2.7). Following this process, the simulation framework was created using a trial base-case study (simple-box design) to assess the different parameters along the developmental process. After this process, the framework was then tested with the selected active commercial vertical farm. Testing a scenario to assess suitability and applicability of this new simulation framework for this context. the suitability and initial reliability of the simulation framework.

The framework was developed with the capabilities of the selected software tool in mind, as well as its limitations. Along the developmental process, the aim was to maximise these capabilities to help further the learning and development of the vertical farming field. This would undoubtedly mean the integration of multi-disciplinary parties from the early design stages of a vertical farms.

Further details of the development of this simulation framework can be found in Chapter 5: "Development of a Simulation Framework for Vertical Farms".

4.3.3 Stage 3 – Case Study to test the developed framework

Following the learning and outputs of stage 1 and 2 described above, a case study was selected, thanks to the scoping study and stakeholder engagement. The amount of data and information required for this case study was particularly difficult to obtain, due to the previously mentioned commercial limitations, data sensitivity and difficulty to find a collaborative organisation. Despite the difficulties, thanks to the significant scoping study, one vertical farm out of the several contacted was open for collaboration and happy to share their monitored data.

As a result, the newly developed framework was tested comparing the real monitored data against the simulated data. The process used a full year dataset, including external variables, such as air temperature and relative humidity, as well as indoors conditions of the growing rooms, such as: the energy consumption from the air handling unit, irrigation system and lighting system. In order to create the comparative scenario for the simulation in HTB2, information regarding the characteristics of the host building was collected and modelled in HTB2. If data was not directly available from the case study, educated assumptions were made based on literature and direct observation during site visits, as well as questioning and discussing with the owner and developer of the vertical farm. This was done with the aim to ascertain as much information as possible, close to the reality of the case study, to develop the equivalent simulated scenario.

One of the areas that will require further development in the future, as an important addition to this simulation framework, is to allow more detail on the representation of the detailed behaviour and impact of plants. At present, for this research this has been significantly simplified, by including the details of plants in one of the occupancy files of HTB2. Nevertheless, to achieve a simulation closer to the reality, the methodology will require to include further detailed data on the behaviour of the plants. Further expertise would be required on a multi-disciplinary collaboration to achieve this in the future. Details can be found in the next chapter.

Subsequently, the data from the monitored case study and the simulations were compared using correlations and descriptive statistics. The analysis included determining what possible parameters not included in the simulation, could be influencing the results, as well as the individual behaviour of each variable monitored vs simulated.

4.4 Chapter summary

This chapter provided the description of the “threefold” overarching research methodology of this PhD (Mixed-methods). The overall PhD research has been undertaken by following these three research methods: (1)Qualitative research, (2)Simulation and (3)Case Study. These methods are convergent, each of them is informing and complementing each other, progressively adding and simultaneously contributing to the overall outcomes of this investigation.

Chapter 5
Development of a Simulation Framework for Vertical Farms

"Through urban agriculture it is possible
to experience urban ornament"

(Viljoen and Bohn 2005)

5.1 Chapter Overview

The literature review (Chapters 2 and 3) alongside the outcomes of the qualitative research approach to the stakeholder engagement (integrated within the literature review chapters and the methodology chapter) demonstrated that there is a significant amount of development in the sector of vertical farming. Nevertheless, there is a need to link the available knowledge and to find a platform to allow the development of holistic models. This is also highlighted in the publications that relate to the topic of simulation of vertical farms, such as Benis and Ferrão (2018) and Khan and Ahmed (2017), where the publications stress on the importance of further development in the area of simulation to assist the design of vertical farms and improve their efficiency. This chapter presents the development of the parameters of a framework for the simulations of vertical farms, using an open-source tool.

5.2 Introduction

Based on published evidence, this investigation has found that vertical farms are a plausible alternative to grow crops inside and outside cities, with a significant amount of advantages attached to it. Yet there is still a lack of availability of information and data in this sector (Avgoustaki and Xydis 2020), as well as the fact that a significant number of vertical farms fail within the first couple of years. Japan being one of the countries that has invested more time and effort in advancing the field of plant factories, is an example that there is still a long way to achieve efficiency in indoor farming: based on a survey by the Ministry of Agriculture, Forestry and Fisheries of Japan, only 25% of plant factories make a profit, 50% break even and 25% run at a loss (Kozai et al. 2016b). Nevertheless, in the second edition of Kozai's book (2019) it is reported that the same survey by the Japanese government established that these figures have improved somewhat: the new report established that 50% of plant factories now made a profit (Kozai et al. 2019). Despite the improved statistics, these figures are not yet encouraging, which begs the question: Are there accessible tools to allow the planning of vertical farms designs before they are built? And if there is a possibility to have these tools, can they be made open sourced and freely available to all stakeholders of the vertical farming community?

These last two questions unveiled significant gaps in the field of vertical farms, and they constitute the importance of objective 2 of this thesis:

> ***Objective 2: To propose, develop and test a conceptual and analytical framework that can be used to recreate or modify the behaviour of vertical farms in indoor environments, with the assistance of a flexible simulation tool.***

Higgins (2016, p.309) published a statement succinctly detailing a number of the issues that are highlighted across the literature, related to some of the gaps of vertical farming:

> There are still a lot of unanswered questions [in vertical farming]. Some of these questions revolve around [the efficiency of] light, but many of them are focused on other variables of vertical farming that are just as important, including seed technology, climate management, water, nutrition, and labour … How does each of these factors play an integral role in making vertical farms both environmentally and economically sustainable?

The statement above, supports two main significant gaps that are highlighted in a number of publications in the field of vertical farming:

1. The need to find solutions to several *unanswered questions.* There are substantial research gaps in this field (Higgins 2016; Khan and Ahmed 2017; Avgoustaki and Xydis 2020)
2. The need to integrate various disciplines and skills that are fundamental for the success of vertical farms (Despommier 2010; Al-Kodmany 2018; Zimmerman-Loessl et al. 2020).

Overall, the evidence presented above and in the previous chapters provide several arguments to support vertical farming as a suitable and viable agricultural alternative in urgent need for optimisation. "vertical farming is not competing against regular agriculture, it aims to be complementary" (Farquhar 2020).

Due to this significant number of parameters that are interconnected in the field of vertical farms, the significance of developing a simulation methodology has been highlighted as part of this PhD investigation. Computer simulations are well known for assisting the investigation and search for viable solutions of complex scenarios, such as the ones posed by vertical farms. Therefore, computer simulations are an attractive and plausible alternative to assist with performance predictions and testing solutions for optimisation.

Effectively, as a result of the literature review conducted (Chapters 2 and 3), this research has been searching for the bridge between the influence of the host building and the behaviour of plants:

1. Research on the behaviour of plants
2. Research on the behaviour of buildings

These two key areas potentially hold plausible possibilities to develop a bridge between the existing knowledge of simulation of the productivity and behaviour of plants growing indoors and the simulation of the indoor environment taking under consideration the influence of building materials, weather, etc. i.e., building performance evaluation.

The above is the key knowledge gap that this PhD work has tackled. However, one of the earlier key references stated here, Ward et al (2018), has highlighted the innate complexity of the integration of plants with their [built] environment. Hence, the approach suggested by this research project is to use a dynamic thermal simulation tool to tackle some of these complexities, whilst being aware of current limitations and therefore providing a method that is flexible enough to allow future integration of further parameters from various other disciplines that can enrich this process and bring it closer to a true simulation platform for vertical farms, which is open source and free of charge for the research community.

The methodology section below describes the exploration and development of a simulation-based framework, which can create a future platform to allow stakeholders from different backgrounds and expertise to communicate, collaborate and share data related to the simulation of vertical farms.

5.3 Software tools for vertical farms

There are a handful of publications providing information about simulation scenario options for vertical farms, but the simulation methods proposed by these authors have their own set of difficulties. Details of these authors and problems are provided in more detail below and in section 5.3.1, some of which have also been previously referenced during the literature review of this topic, in Chapter 3 (section 3.4).

Just to highlight a few of these examples and attached difficulties; Shao et al (2016) developed virtual vertical farming scenarios, in their attempt to test a new software tool they developed to assist the financial estimation of VF. Some of the perceived challenges of using this software tool (called VFar) are mainly attached to the development of a bespoke software, it has significant limitation on its capabilities and the level of assumptions can make the results questionable, in terms of how close to reality are those results. The above publication only reported using their simulations on fictional scenarios, not real vertical farms. Similarly, most authors currently working on simulation of vertical farms work only on fictional scenarios (Benis et al 2017b and Graamans et al 2018). The publications reporting results on data of real vertical farms (or empirical) are tackling the area of monitoring and analysis of data, not relating it to any simulated scenarios (Ward R et al. 2018 and Jans-Singh, M. et al. 2019). Furthermore, added to the limitations of the current body of knowledge of this are, none of these methods have been validated, this is understandable due to the early stages of this work in an area that is still in its infancy.

Despite any shortcomings, these authors have been pioneers in the development of simulation of vertical farms. In their publications they highlight the limitations of the proposed modelling scenarios and acknowledge the urgent need to develop this area further. As previously mentioned, this is a highly multidisciplinary field, as such, in order to achieve optimum outputs, true collaboration ought to take place. Jans-Singh et al. (2019) describes that "there is a lack of understanding of how well these [vertical farms] systems can be integrated into existing infrastructure, and how their environment can be optimized in an efficient manner. Scientific models for plant growth are largely empirical and developed for certain types of commercial plants" (Jans-Singh et al. 2019). Furthermore, the influence of the host building on vertical farms is even less researched and the understanding of the interaction between buildings and plants is more limited compared to the plant's growth models. Hence there is a significant potential in the area of integration of the relevant building parameters that affect the overall environment of a vertical farm.

These parameters in relation to the behaviour of plants and how they have mutual influence must be approached in a dynamic manner.

5.3.1 Exploration and scoping of a viable software tool

Software tools used to simulate the built environment have significant potential for knowledge-transfer into the field of vertical farming. Nevertheless, exploration in this area of vertical farming has been minimal (Benis et al. 2017b; Graamans et al. 2018). The authors Citherlet et al (2001) once described how to achieve "advance architectural development". Complex domains of the built environment such as heating, light, ventilation and acoustics can only be truly understood and realistically considered when the interaction amongst all of these parameters is taken under consideration. Without an integrated approach, individual analysis will not reflect the real scenario (Citherlet et al. 2001, p. 451). Although, the above concept is referred to as "advance architectural development", the same principle applies for vertical farms: there must be an integrated approach.

The multifaceted nature of vertical farms requires a similar problem-solving approach to building performance. Building performance simulations do not consider the physics of buildings alone; they also consider the complexities of the interactions of humans (and other living beings) as well as several other actively influencing parameters that inhabit the building. This characteristic makes this approach an enticing candidate for further exploration on how the current boundaries of building performance simulation can be pushed beyond their current uses. This is particularly important given the fact that the vertical farming sector lacks a platform that can help towards achieving a holistic analysis approach. "Given the complex environmental, economic and social dimensions of urban agriculture, holistic decision support tools could help integrating them in urban areas" (Benis and Ferrão 2018, p. 36).

The significant potential for knowledge-transfer from the fields of architecture and the built environment has not been unnoticed in the research world. Work has been undertaken by a few people on this area, for instance Benis et al. (2017) and their work on Building integrated

Agriculture (BIA) development of a simulation-based decision support workflow for the implementation of Building-Integrated Agriculture (BIA), Graamans et al. have worked on simulations attempts comparing greenhouses and plant factories and comparing resources efficiencies (Graamans 2015; Graamans et al. 2018), and Khalil and Wahhab (2020) exploring the use of ENVI-met to assess the potential of the integration of vertical farms in cities to help to mitigate the Urban Heat Island (UHI). The few examples above, are evidence of the variety of approach that evaluating vertical farms can take and the number of concepts that are closely linked to this field. One particularly relevant aspect that can be highlighted from the examples above that is particularly influential in the area of simulation, is the scale of the analysis: a research can have two completely different scopes of simulation: Building Level or Urban Level (Benis et al. 2018; Khalil and Wahhab 2020).

There is little comprehensive evidence of advancement in the area of simulation development for vertical farms, at both levels: Building and Urban Scale. During the literature review, most authors agreed that this is an area significantly underdeveloped, and that more work is necessary. For instance, Avgoustaki and Xydis (2020) discuss the matter around computer simulation models and adaptive analysis software tools, expressing the significant need to undertake "more research [and development] focused on the extension of [these] programs and modify the already existing ones" (Avgoustaki and Xydis 2020, p. 265). Similarly, Ward R et al (2018) describes that the "simulation science of controlled environment [or vertical farms] is yet to mature. Testing models against data from more urban farm typologies will continue to improve the response of the model under different scenarios. Ultimately, this will enable an improved understanding of the city-scale environmental impact of integrating urban farming within cities" (Ward R et al. 2018, p.282). Benis et al. (2017) also agree with the need of vertical farm simulations to be further developed, in their work it is highlighted the significance of considering the building envelop in order to "lessen heat losses and gains, thus reducing energy requirements for climate control." (Benis et al. 2017, p.600).

As a result of the information and facts retrieved during the exploratory stage of this PhD research, the idea of developing a simulation framework for vertical farms was born, given that the author has some previous experience with computer simulation modelling (Bassett and Waldron 2013; Jones et al. 2013; Waldron et al. 2013). This idea originated with the intention to develop a potential tool that can help plan and provide a method to integrate various aspects of vertical farming at an early stage, in a virtual platform. This simulation framework aims to provide an initial stage towards a holistic approach aiming to find ways to optimising the design of vertical farms before any financial investment has been made.

Significant progress in the area of simulation has been published by Graamans et al (2015, 2017, 2018, 2020) trialling software tools (MATLAB and DesignBuilder) to recreate the environment of vertical farms. Their investigations tackle a number of important aspects of crop behaviour, with a particular focus on the role of plants to calculate the energy balance equation. They declare that evapotranspiration is a relevant design parameter that is often ignored in plant factories calculations (Graamans et al. 2017). Their particular work on crop transpiration and energy balance included parameters relevant to the behaviour of the plants, such as the effect of net radiation in plant production, surface (stomatal) resistance and aerodynamic boundary layer resistance and transpiring leaf area, the leaf area index (LAI) (ditto). On a separate study, (Graamans et al. 2018) developed a study comparing simulation methods between greenhouse and plant factories. In this occasion the MATLAB method they have published the previous year was not used, but instead two different software approaches: KASPRO for greenhouses and DesignBuilder for plant factories. This investigation has shown an interesting approach to learn from the potential wealth of knowledge that can be transferred from greenhouse into vertical farms, since simulation methods of greenhouses are significantly more advanced (Vanthoor et al. 2011a; Vanthoor et al. 2011b; Shamshiri et al. 2018).

Nevertheless, the methods described above still require further development and upgrading. One of the issues identified here was that the authors described DesignBuilder as not a dynamic simulation tool

(Graamans et al. 2018, p.32). However, this is not the case, this study simply chooses not to use it as a dynamic simulation tool. When contacted as part of this research stakeholder engagement, the authors responded the query by explaining that vertical farming modelling does not require dynamic simulation because it only has two states: photo-period and dark-period with constant climate throughout. Nevertheless, with this description they seem to ignore altogether the impact of the outside weather on the indoor environment. This simulation model therefore assume that vertical farms occur only on perfectly sealed building. This is however a common assumption in the field of vertical farm publications (Kozai et al. 2016b).

Building performance evaluation and simulation is a well-known area of research in the architectural world. It exists due to the fact that buildings rarely perform as expected and that there is a massive difference between "as-designed" vs "as-built" constructions (Zero Carbon Hub 2014; Jack 2015). It is relatively safe to assume that this is likely to be the case also for buildings containing vertical farms. The influence of the outside weather and the materials of buildings is often just neglected in the analysis and understanding of vertical farms (Kozai et al. 2016b). Publications that do consider the impact of the outside climate/weather, as well as the design and materials of buildings, on the indoor environment of vertical farms tend to describe their work as Building Integrated Agriculture (BIA). Benis et al (2015, 2017, 2018) are some of the most published researchers in this area, focusing on computer simulation mainly of hypothetical scenarios. These publications focus on comparative studies of various forms of urban agriculture, vertical farms being one of them. They used an architectural 3D modelling program called Rhinoceros 5.0TM with its plug-in GrasshopperTM which "enables the use of numerous environmental analysis plug-ins such as Diva-for-Rhino, that are based on the validated daylighting and thermal simulation engines DAYSIM and EnergyPlus." (Benis et al. 2017b). Nevertheless, the tools presented above can be significantly costly, limiting therefore the number of people that will be able to use them.

Similar to the work described above, Khan and Ahmed (2017) also presented a proposed simulation method for vertical farms by exploring the capabilities of Building Information modelling (BIM). Nevertheless, the software used in this study can also represent a significant cost. In order to create a common platform to communicate at an international level with the vertical farming community, the issue of affordability should also play a significant role.

This PhD project required to establish research boundaries in terms of possible simulation routes to explore. The number of potential alternatives that can be explored as part of the developmental process of a simulation framework for vertical farms represent a significantly large area of research. One PhD project cannot cover all the domains that are influential to vertical farms, as it has been demonstrated with the information presented above, this is a multifaceted area which requires several different expertise to work in collaboration. Therefore, keeping in mind that one of the aims of developing this simulation framework is to layout a path to unify knowledge in this field, the bullet points below present some important items that influenced the decision-making process of selecting the simulation pathway. These bullet points became therefore the selection boundaries of the chosen software tools, and these are based on the identified gaps of the literature and sector engagement:

- Flexibility of the chosen software tool(s): Due to the complexity of vertical farming, the software used as part of this simulation framework should be flexible enough to allow the integration of the various domains or relevant parameters that are integral parts of the holistic representation of vertical farms.
- Open-access and/or Low cost: There is significant evidence supporting the fact that one of the major obstacles of the development of vertical farms is the capital cost (Thomaier et al. 2014; Kalantari et al. 2017b; Al-Kodmany 2018; Hughes 2018; Avgoustaki and Xydis 2020). In order to have a successful integration of this simulation framework, the financial aspect must be minimum, i.e., the use of expensive simulation software tools can potentially render this exercise useless. Therefore, the financial

implications of the software used is given a significant weight in the selecting process. If there is a tool that is fit-for-purpose, with the same level of validity and quality of the calculations and is potentially open source and free of charge, this tool will be given priority to be selected for this investigation.

- Generalisability: It is described as "… how well a method, measure or measurement, and data from that method, will generalise into other domains, situations, settings or populations" (Wilson and Sharples 2015, p.27). It has been mentioned that in the field of vertical farms is a common assumption to ignore the impact of the outside weather, which raises concerns about the generalisability of these models in different contexts.
- Reliability: refers to questioning if "… we would get the same results and interpretations if we repeatedly use a method or measure" (Wilson & Sharples, 2015b, p. 26).
- Usability: Characteristics such as accessibility, efficiency, effectiveness, and satisfaction are requirements to engage the end users with a software (Wilson & Sharples, 2015b, p. 234).
- Validity: is defined as "…whether something measures what it claims to measure" (Wilson & Sharples, 2015b, p. 26). Simulation tools are built to predict performance, running costs, behaviour, amongst others. Therefore, a validated tool would support the reliability and generalisability factors.

5.3.2 Software tool selection stages

Based on findings described above and to select the software tool to be used as the foundation for the simulation framework developed in this doctoral research, three key issues have been considered:

- Literature review outcomes: Some of the software tools found during the literature review show promise of future development in this area. Nevertheless, all the different methods have their own limitations, therefore the decision has been made also considering these limitations (section 5.3.1 and Chapter 3 section 3.4)

- Sector engagement outcomes: the author of this thesis contacted two of the most published authors in this area: Luuk Graamans (2015, 2017, 2018, 2020) and Khadija Benis (2015, 2017a, 2017b, 2018a, 2018b). Further information has been gathered as part of this process, which also informed the final choice. Based on these conversations, it became evident that Graamans' simulation methods have a significant focus on plant biology and less on building physics. On the other hand, the models presented by Benis are very diverse and do not focus only on vertical farms but also on greenhouses and other building integrated methods of agriculture.
- Based on professional experience with different software: The author of this thesis identified which software tools that she has experience with, could potentially be used for the purpose of vertical farming. Some of the possible options are: HTB2, Ecotect, DesignBuilder and Virvil plug-in for SketchUp. Nevertheless, further experimental attempts were also undertaken with other potential software tools, such as ENVI-Met, Solidworks and Versim. The three latter were completely new to the author, therefore she received a tutorial session from expert colleagues to understand the features of the tools. During these introduction tutorial sections, the author identified ENVI-Met, Solidworks and Versim to be too rigid to be able to integrate the full design of vertical farms.

  The author does have professional experience with HTB2, Ecotect, DesignBuilder and Virvil for SketchUp, see below for a detailed recount on the final selection process for the chosen tool.

In order to select the software tool (or tools) to assist the development of this framework, the author used an elimination process, whereby the tools outlined above were considered and explored in order to understand their potential to achieve the purpose of this work.

- DesignBuilder requires the purchasing of a license which costs significantly and varies between £649 up to £2,499 depending on the complexity of the required simulation. As established during this research, it can be expected that simulation of vertical farms can be expected to be relatively complex, potentially costing the maximum price of this license. Therefore, the significant cost of this tool made this an unsuitable option for this framework development.

- Rhinoceros 5.0™ requires the purchasing of a license (minimum cost €995) (Rhinoceros™ 2020). The grasshopper plugin is included in with Rhino 6, but to get the Diva-for-Rhino, it costs a further $950 (Solemma 2020). As stated above, financial requirement to purchase software tools will make them less viable candidates for the development of this framework. The aim of this investigation is to develop a method that can be freely distributed across the international vertical farming community. Therefore, a software that is free of charge and open source will take precedence.
- From 2015, licences to purchase Ecotect have been discontinued (Autodesk Support 2016). Aiming for longevity of this framework, selecting a software that has been discontinued is not recommended. Hence Ecotect has been discarded.
- HTB2 (Heat Transfer in Buildings (version2.0)), is an open source simulation software that has been used in the research community mainly for the analysis of the thermal behaviour of buildings and energy consumption, prediction and optimisation modelling, as well as sustainability parameters (Lomas 1996; Bassett et al. 2012; Jones et al. 2013). It uses mathematical models and laws of physics to calculate internal temperature, predict energy consumption and humidity, among others. While it has not been used for recreating the conditions of vertical farms, its characteristics present potential uses within this field, since it allows factoring multiple variables. About HTB2, Bojic et al. expressed the following: "In the study, the dynamic building energy model HTB2 was used to predict the cooling loads and indoor environmental conditions in the investigated flats throughout the year. The model uses the finite difference method to solve the one-dimensional dynamic heat-conduction equation for modelling heat transfer through the envelope and partition elements. This building energy model can calculate a thermal performance of a building with multi-room flats exposed to time varying climatic and occupation conditions. The handled climatic parameters are outdoor temperature, solar gain, and shading. The

> model allows the user to define occupancy pattern, complex cooling and heating (cooling), ventilation and infiltration schedules, and lighting and internal load intensity patterns. In addition, it allows varying control settings during run-time, to mimic realistic occupation conditions. Predictions of HTB2 have been found to be matching well with measurements in buildings in cold and hot climate [12,13]." (Bojic et al. 2002).

HTB2 as the selected simulation tool

The main characteristics required for a computer programme to tackle the kind of issues addressed before are flexibility and reliability. Most commercially available software is expensive, and their code is not usually open source. Furthermore, some of the assumptions made by them is that there is little or no control over the number of required variables (i.e., 'black box'). Therefore, as a result of the selection process, the main reasons to choose HTB2 are:

- **Open-source Software:** HTB2 was developed by the research community for the research community. This means it is open for other researchers or interested parties to make the best use they can from this software tool. Due to this nature, the software is not a commercial tool. Therefore, the power of this tool is on its engine and computational capacity, but not particularly strong on its user interface.
- **Flexibility**: This is potentially the most significant characteristic of this software tool to be used to simulate vertical farms. This is due to the gap in the research world of a particular simulation tool that can attempt the unification of the different aspects (or domains) of vertical farms. HTB2 is "characterised by a highly modular structure in which different processes are clearly separated so allowing the addition and substitution of alternative algorithms to be readily made." (Lewis and Alexander 1990, p. 7). The author of this thesis would like for this research to be a first step towards developing this software platform further, with the focus of vertical farming simulation and optimisation (as an early-stage design tool or aiming

to optimise existing designs/operational vertical farms). This software has good potential for further expansion of its current capabilities.

- **Future potential development**: Due to the flexibility of HTB2, future projects have the potential to achieve great lengths in exploring further capabilities of HTB2. If developed with a multi-disciplinary team focused on the essential aspects of vertical farms, a group of researchers/developers from backgrounds such as computer programming, plant biology, mathematics, biochemical and physics will possess the necessary knowledge the development specific modules that can be added to the initial HTB2 structure. "The availability of a more flexible open modelling system … that would allow algorithms developed by different groups to be freely interchanged and combined has … become a priority in the building science field" (Lewis and Alexander 1990, p. 7).
- **Validation**: This software has been under development since the 1980s, it has been validated and it has undergone a series of upgrading and development throughout the decades.
- **International Use and Availability**: There are several research projects that have been published with case studies around the world demonstrating the current applications of HTB2 and its reliability (Lomas 1996; Yik et al. 2002; Khodakarami et al. 2009; Hassan et al. 2011; Shahidan et al. 2012; Jones et al. 2017; Huang et al. 2020). As mentioned before, this tool has been mainly used for the analysis of energy consumption of buildings under several different contexts, but without the focus required for vertical farming analyses, until this research project.
- **No financial cost**: This software tool can be requested free of charge from the Welsh School of Architecture, Cardiff University. It is also available to download online directly from a Cardiff University webpage which contains information about HTB2, although this portal is focused on a sibling software tool known as VirVil (A plug-in for SketchUp which uses HTB2 as the calculation engine and SketchUp as the user interface) (Welsh School of Architecture 2014).

- **Literature resources to support** the use of HTB2 are published and available: Literature with details of the structure of this software tool, as well as information to learn to use this software is also published (Alexander and Lewis 1985; Alexander 2008).

One of the most important characteristics for HTB2 to be selected as the suitable simulation tool, is the flexibility it allows to let the user handle the parameters required. In terms of vertical farming there are a number of conditions that will require intrinsic simulation, and a great number of them need to be analysed in a different fashion, i.e., the thermal behaviour of the building hosting a vertical farm would require a different analysis process to the one predicting/analysing the behaviour of the plants and moisture. These are issues that are being explored in this research project.

In summary, following the process detailed above, HTB2 has been selected as the base of this framework which aims to simulate and predict the performance of vertical farming buildings.

5.4 Methodology for the development of the Framework: Using a Base-Case Study

Using the information gathered above, an analytical, conceptual, and holistic framework is proposed in this section in order to encourage vertical farm stakeholders to use this method to integrate their expertise into one holistic pathway of early-stage vertical faming assessment. This framework is assisted by the chosen software tool: HTB2. It also aims to integrate existing knowledge into the process, in the spirit of getting a step closer to achieving transparency and ease of communication in this field, which can eventually lead to a further collaborative development of this framework, targeting a holistic approach to vertical farming integration in the built environment.

Following the above, the next stage is to define a (simplified) case study to assist the development of this framework. Therefore, for the purpose of this investigation a virtual base-case study has been designed to help with this developmental stage of this framework. The characteristics are described in the following section.

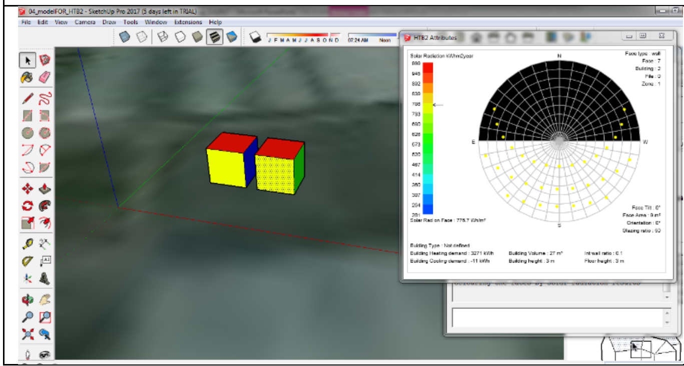
5.5 Results and Discussion

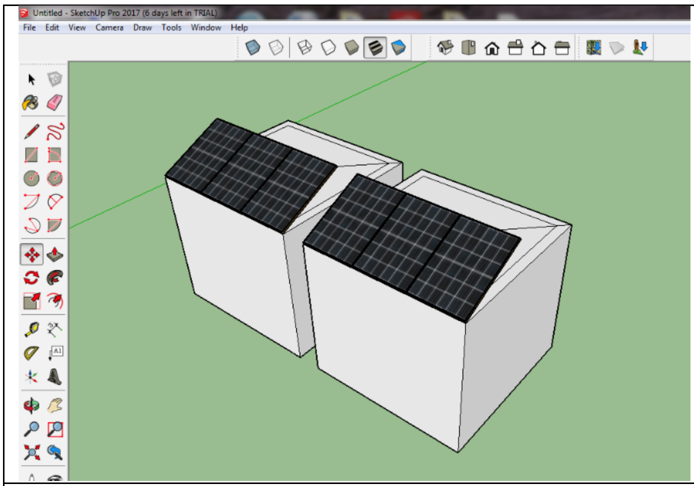
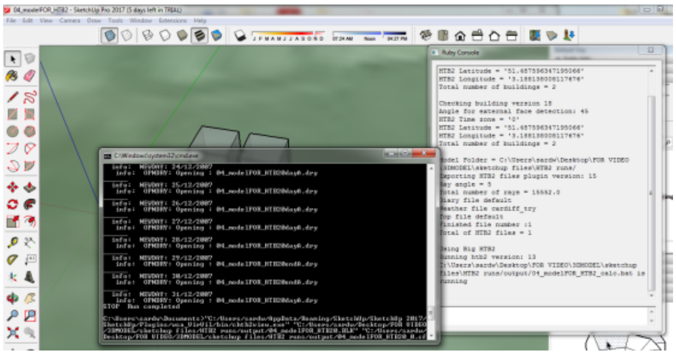
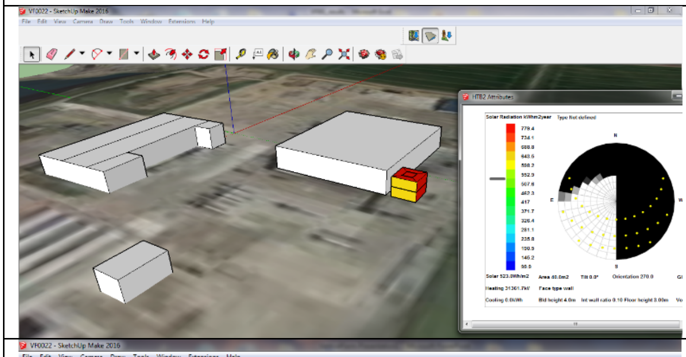
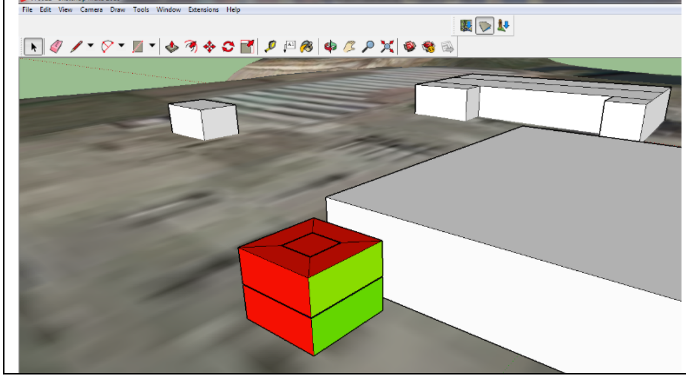
The sections below describe the development process of the simulation framework. A base-case study is proposed and used as a kind of "Guinea pig" to facilitate the process and make decisions about the description of all the parameters required to scope the HTB2 software tool.

5.5.1 Simulation Framework

As mentioned in the methodology, the development of the framework was made using a "Base-Case" study. In the first instance, the opening trial of the case study took place using the more user-friendly interface of HTB2: Virvil Plugin for SketchUp (Waldron et al. 2013; Welsh School of Architecture 2014). Nevertheless, Virvil provides a set of default characteristics that are not as easy to alter by using this interface alone. When the data requires customisation and changes, this interface added a higher level of complexity to the basic files. Therefore, after running a few trial tests with Virvil SketchUp (Table 8), the decision was made to run the base-case study using directly HTB2, without the use of Virvil SketchUp interface.

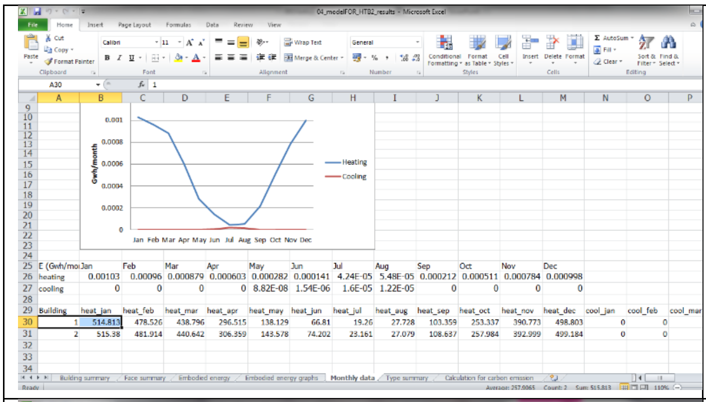
Table 8. Exploratory scoping study to assess the suitability of Virvil Pluging for SketchUp as the interface to use HTB2 in this vertical farms framework.

Visual Snapshot of Study	**Description**
 Face type : wall Face : 7 Building : 2 File : 0 Zone : 1 Solar Rad on Face : 778.7 Wh/m² Face Tilt : 0° Face Area : 9 m² Orientation : 0° Glazing ratio : 60 Building Type : Not defined Building Heating demand : 3271 kWh Building Cooling demand : -11 kWh Building Volume : 27 m³ Building height : 3 m Int wall ratio : 0.1 Floor height : 3 m	Scoping study assessing the potential of developing the base-case for this framework by using the Virvil Plugin for SketchUp, connecting the 3D model to the HTB2 calculation engine.

	Two cubes were drawn side to side to undertake comparative exploration of the two spaces. Photovoltaic panels were also integrated, in the scoping study to gauge the potential of renewable energy in the analysis also.
	This analysis found that these initial trialled case studies, ran successfully using the HBT2 engine within the SketchUp environment. However deeper investigation revealed that this was not the most appropriate tool for the desired context. Further explanation below.
	This is the view of a different case study that was also explored. This was a case study to appraise the potential to integrate a vertical farm case study with an Anaerobic Digestion (AD) plant (in Bridgend, Wales).
	This is another angle of the case study mentioned above. It was a scoping study to co-locate the base-case study next to an AD plant. As part of the stakeholder engagement of this project, the AD plant company (Cenin) was contacted to undertake the feasibility study.

```
Total number of buildings = 2

Checking building version 15
Angle for external face detection: 45
HTB2 Time zone = '0'
Total number of buildings = 2

Exporting HTB2 files plugin version: 15
Total of HTB2 files = 1

Running htb2 version: 13
```

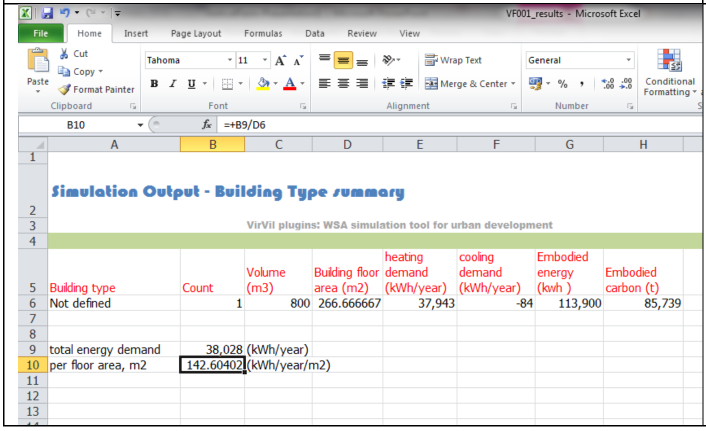
```
STOP  Run completed
```



E (Gwh/mo	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
heating	0.00103	0.00096	0.000879	0.000603	0.000282	0.000141	4.24E-05	5.48E-05	0.000212	0.000511	0.000784	0.000998
cooling	0	0	0	0	8.82E-08	1.54E-06	1.6E-05	1.22E-05	0	0	0	0

Building	heat_jan	heat_feb	heat_mar	heat_apr	heat_may	heat_jun	heat_jul	heat_aug	heat_sep	heat_oct	heat_nov	heat_dec	cool_jan	cool_feb	cool_mar
1	514.813	478.526	438.796	296.515	138.129	66.81	19.26	27.728	103.359	253.337	390.773	498.803	0	0	
2	515.38	481.914	440.642	306.359	143.578	74.202	23.161	27.079	108.637	257.984	392.999	499.184	0	0	

These are some of the results drawn from using the Virvil Plugin. Nevertheless, they do not reflect the focus required for vertical farming.
This tool (Virvil Plugin) was initially designed for large urban scale case studies. Hence, its scale is not yet relevant for the vertical farming field (individual building assessment)



B10 =+B9/D6

Simulation Output - Building Type summary

VirVil plugins: WSA simulation tool for urban development

Building type	Count	Volume (m3)	Building floor area (m2)	heating demand (kWh/year)	cooling demand (kWh/year)	Embodied energy (kwh)	Embodied carbon (t)
Not defined	1	800	266.666667	37,943	-84	113,900	85,739

total energy demand	38,028	(kWh/year)
per floor area, m2	142.60402	(kWh/year/m2)

This is another view of some of the initial results from the scoping case-study. This method can potentially be useful in the future, when simulation of various vertical farms will be required at an urban scale. Nevertheless, for an assessment at a building-level, it is better to use HTB2 directly, without added interfaces.

5.5.1.1 Framework Phase 1: Definition of stages

This section will describe the various parameters examined and chosen during this developmental stage of the framework based on the HTB2 structure. HTB2 has a Top File that connects all the sub-files, in Figure 17 is showed the upper part of the hierarchy of HTB2 with the 4 main headings of the different sections that are currently comprised in this software tool: Building, Services, Diary and Meteorological.

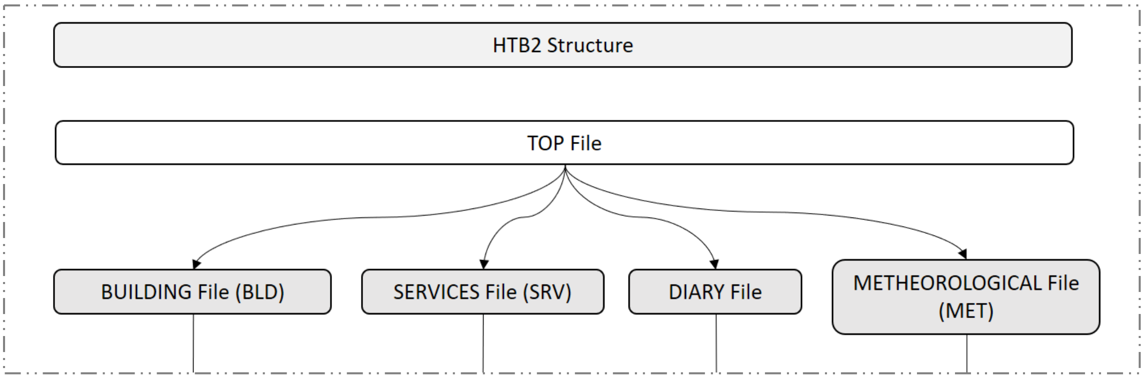


Figure 17. Upper part of HTB2 top file

In summary, the 'TOP File' links those four sections and all the characteristics contained within those files.

Stage 1: THE BUILDING

The first stage is to establish the characteristics of the host building. The virtual base case study has been outlined as a simple box-like building, the simplicity of this has been necessary, due to the fact that this is the first time that this simulation methodology has been undertaken in the context of vertical farms.

The first scenario evaluates a simplified building in the shape of a cube, with the dimensions of 3 meters on all sides, with a total footprint: 9 m^2 and total volume: 27 m^3. The building is assumed not to have any windows for this development scenario (all walls and ceiling are opaque). Nevertheless, HTB2 offers the possibility of including windows also.

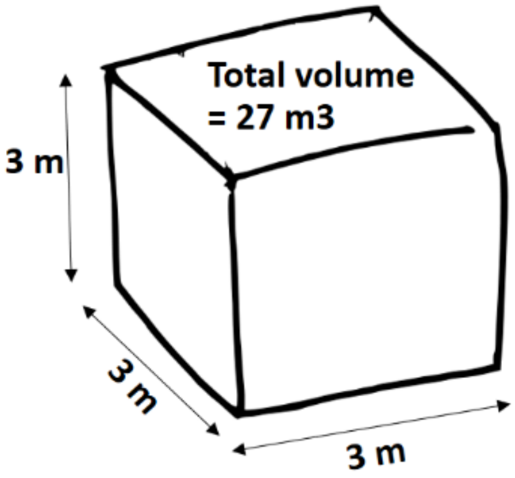
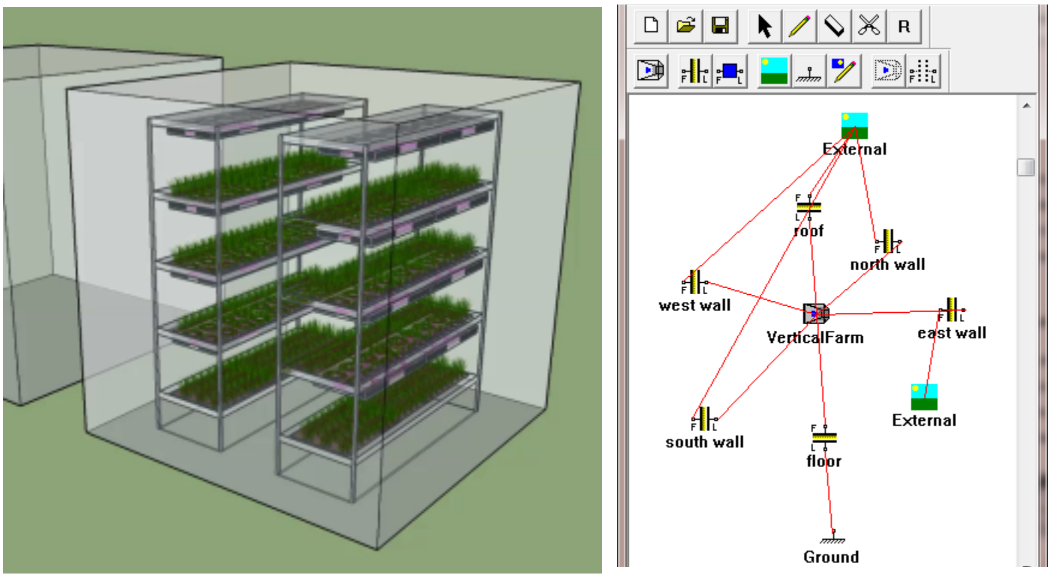


Figure 18. Building volume

Figures 18 and 19 provide visual representation of the base case study. Figure 18 provides the basic measurement and Figure 19 provides the view of the case study using two different software tools: (a) SketchUp and (b) HTB2.



(a) (b)

Figure 19. Graphic representation of the virtual base-case study. This is viewed in two different interfaces: (a) SketchUp and (b) HTB2.

As it can be seen in Figure 19, the visualisation of the same case study looks significantly different on each interface. The SketchUp based interface depicts a scenario visually more similar to the real setting. However, the schematic representation provided by HTB2 highlights the important links between the different elements of the building, which will thereafter have an impact on the indoor environment of the building. Despite of the 2D visualisation option provided by HTB2, the graphic representation of the physical model in this tool is relatively simple and easy to learn and understand.

As part of this stage, the inner arrangements of the building are established. The layout of the growing trays inside the base-case study have been informed by literature (Kozai 2013a; Li et al. 2016; Tsitsimpelis et al. 2016), based on the most popular layout of indoor vertical farms, an array of growing trays have been chosen for this simulation (Figure 20).

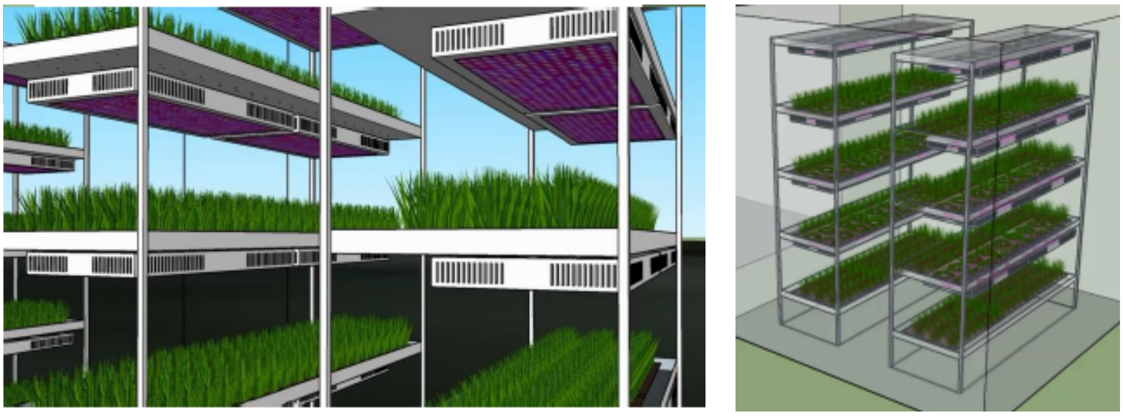


Figure 20. Plant tray arrangement for the base-case scenario

Based on the parameters found on the literature, the best sizes and distances between growing trays/shelves vertically and horizontally have been selected (Kozai 2013a; Li et al. 2016; Tsitsimpelis et al. 2016) and the final characteristics for this case study are specified in Table 9.

Table 9. Characteristics of the shelves dimensions

Trays/shelves length = 2 m
Trays/shelves width = 0. 6 m
Trays/shelves Thickness = 0. 06 m
Trays/shelves Distance = 0.3 m
Total Planting tower height= 1.8 m
Number of stack/towers = 2

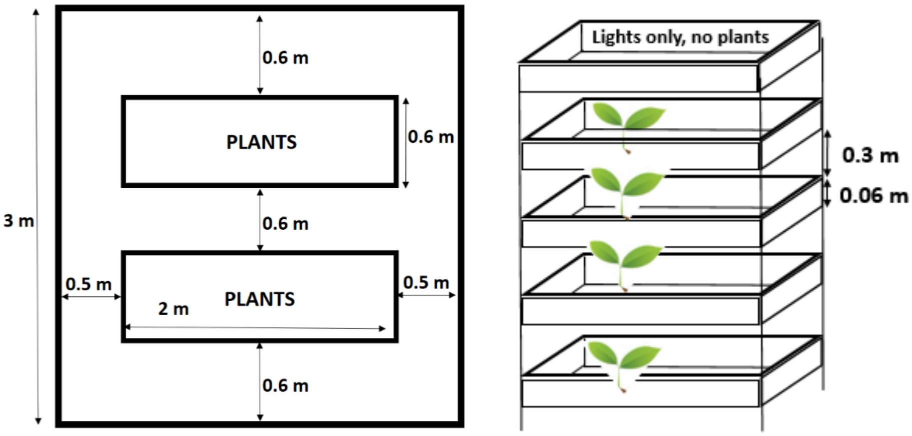


Figure 21. (a) Plan view of the base-case study indoor planting trays layout (b) schematic of the growing trays.

Figure 21 shows the plan view of the building, which includes the location and distances of the growing trays within the vertical farm as well as a simplified diagram of the growing trays to show distances and thickness.

The HTB2 simulation requires a location in order to include the weather file. Therefore, before detailing the model further, our case study is given a location (Figure 22). This study assumes that the weather file will influence the thermal performance of the vertical farm, as it does on most buildings, even when indoor control environment is integrated (Oldewurtel et al. 2012). For the base case study, the chosen location is:

Cardiff, United Kingdom
- Latitude: 51.48
- Longitude: -3.19

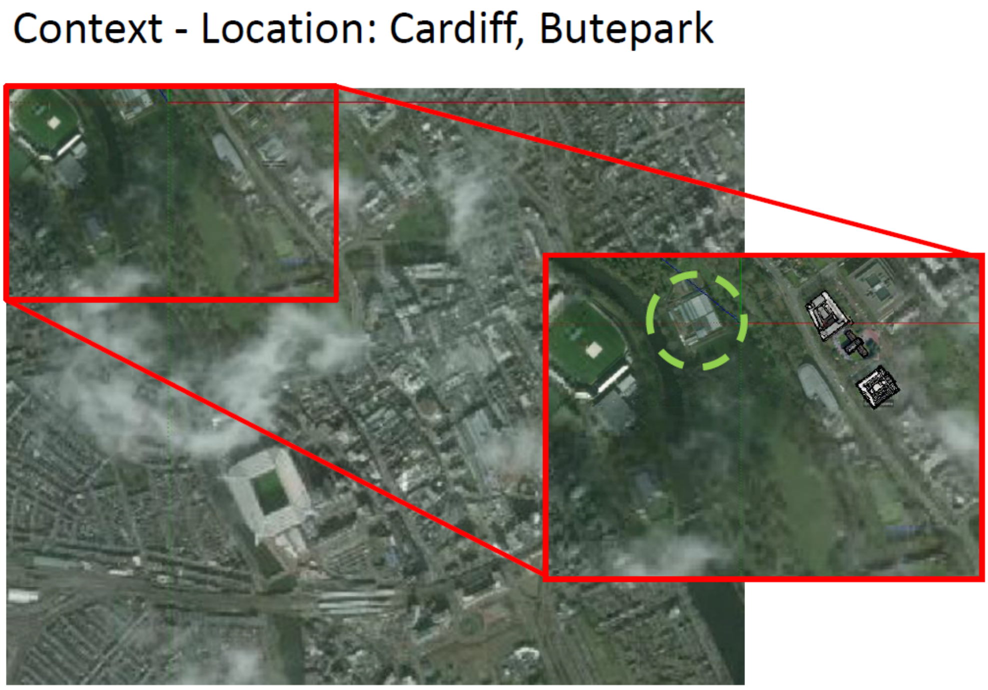


Figure 22. Location of the building

Stage 2: SERVICES

This stage consists of detailed information regarding the services required to run the building successfully to allow the crops to thrive. For instance, heating requirements, ventilation, lighting, occupation patterns (i.e., number of plants and humidity levels). Finally, this section should also cover water requirements, however, this specific feature has not been yet incorporated in this methodology. This stage will be considered in detail in the section “detailed parameters”.

Stage 3: DIARY

This stage refers to the ‘diary files’, i.e., the timetables relevant to the running of the vertical farm. For instance, the process requires to know an approximate number of plants that will be in the building, during what period of time. This is to further estimate the amount of moisture produced by these plants. This information will allow the simulation to consider moisture levels of the vertical farms, hence looking to maintain the appropriate level of humidity for the type of vertical farm.

Stage 4: WEATHER DATA

This part of the methodology keeps all the climatic information needed for the simulation period (own data files can be uploaded, otherwise this process allows to use weather data files from EnergyPlus).

5.5.1.2 Framework Phase 2: Parameters

The software tool selected for this framework (HTB2) encompasses a calculation hierarchy containing sub-routines of various nature. This framework development takes advantage of this hierarchy in order to guide the different phases along a similar route of the architecture of the software (Figure 23).

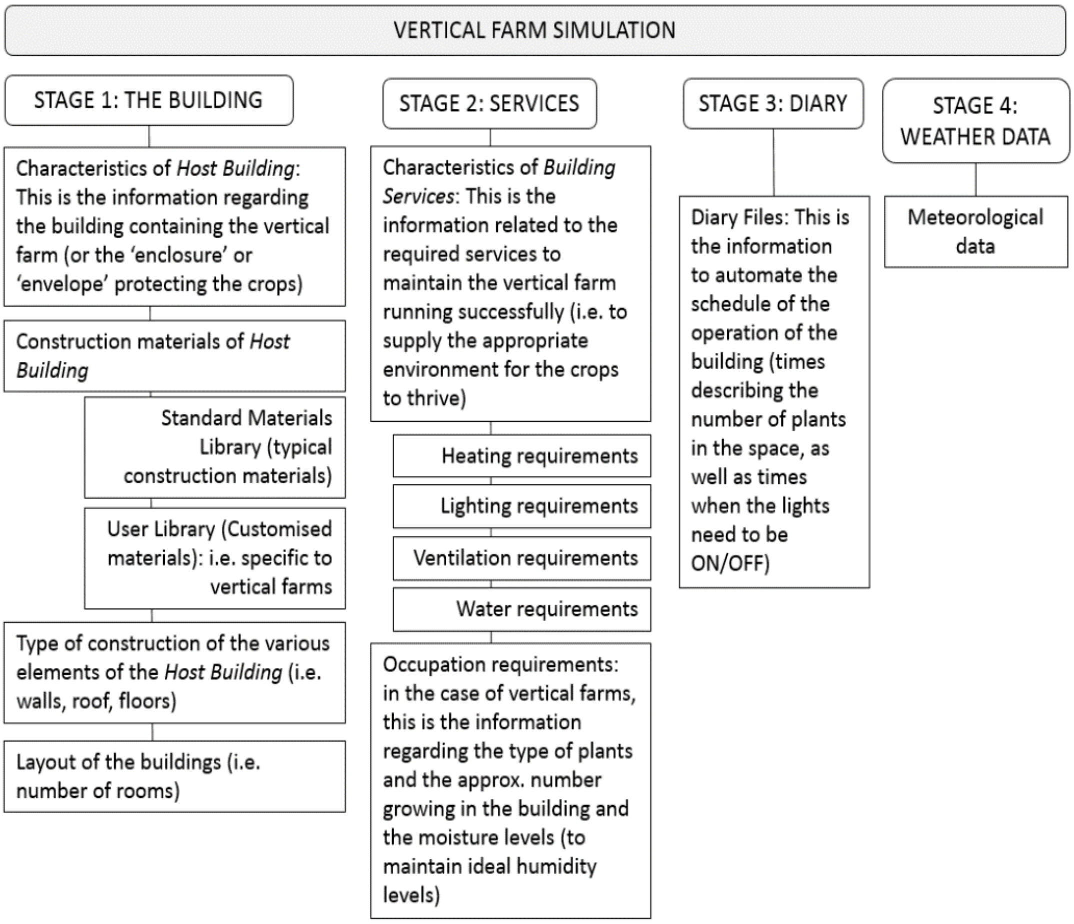


Figure 23. HTB2 Structure which has assisted the development of this framework methodology

As it can be seen in Figure 23, this software (HTB2) is constituted by a number of "modules" that have never been explored with the focus of vertical farms, hence the purpose of this investigation to evaluate its potential. The development of this framework also benefited from the flexible nature of HTB2 (Lewis and Alexander 1990), where the most relevant modules were identified in Figure 24. The base-case study (previously described in Figure 18) has been used to aid the conceptual and descriptive development of this framework.

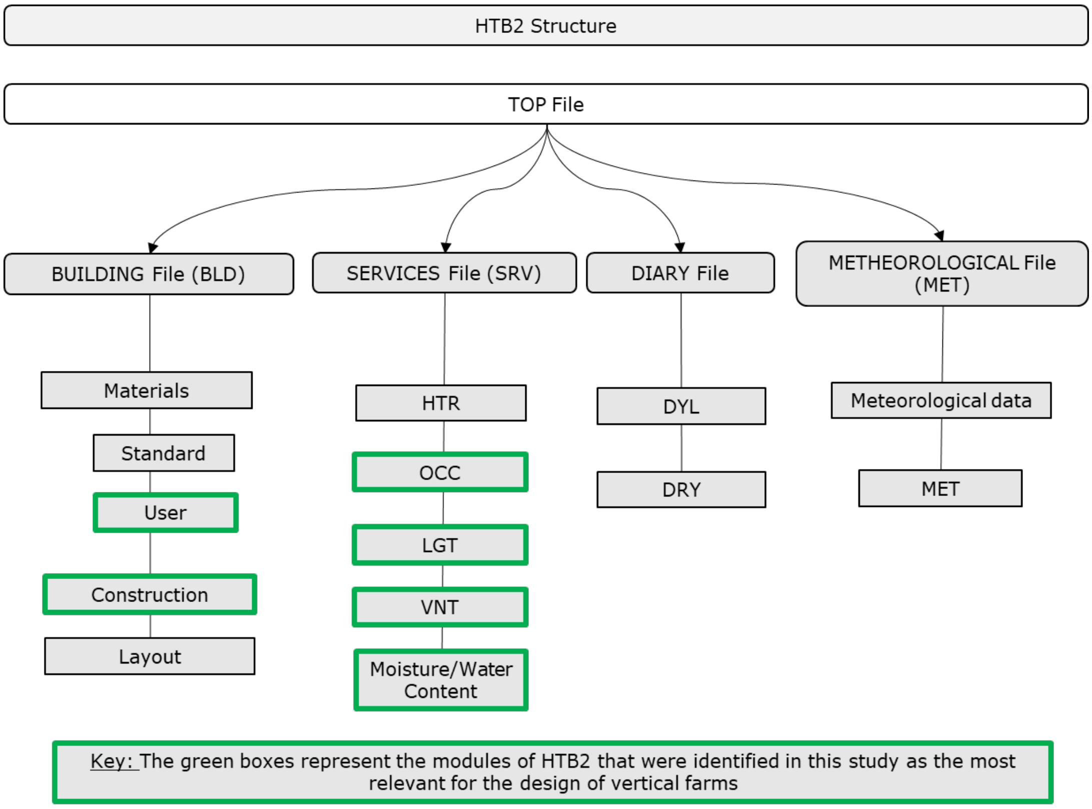
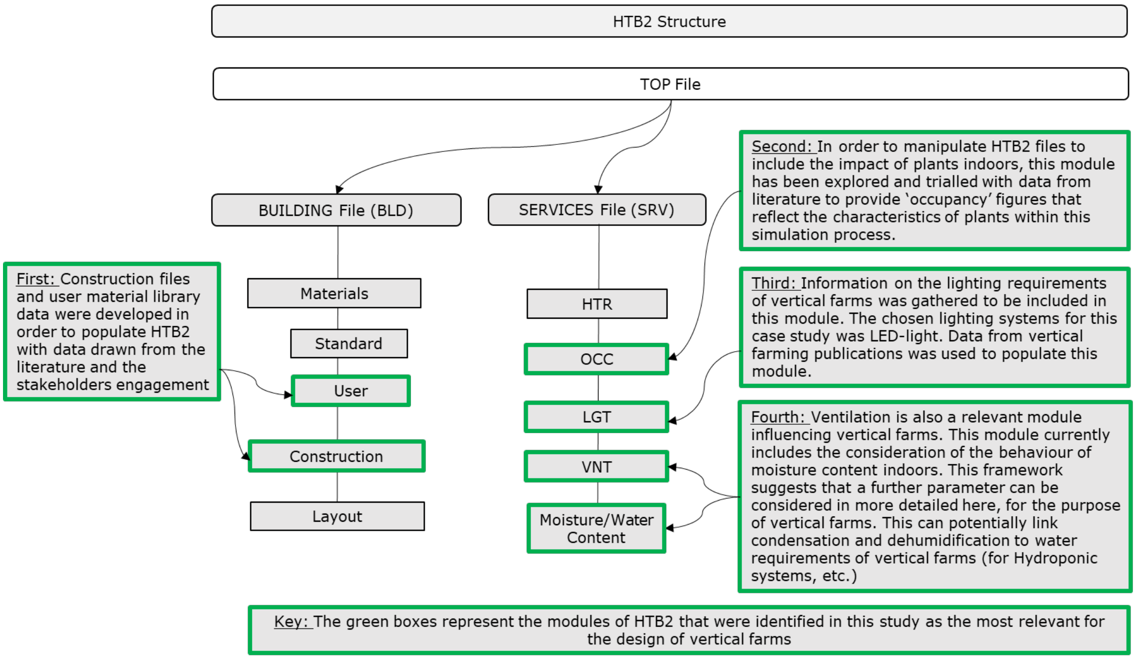


Figure 24. Simplified HTB2 Structure with the modules identified as most relevant for the development of this framework.

Figure 24 depicts a simplified structure of the HTB2 modules, where the most relevant ones for vertical farming simulation have been highlighted in green. The next step of the analytical process of this framework development is thereafter described in Figure 25, where further details are provided on the focus of the selected modules, identified as most relevant. In order to populate these modules with vertical farming data, a spreadsheet was developed with information gathered from the literature review and stakeholder engagement. A summary of this spreadsheet can be seen in Table 10. The data was classified under some of the most relevant parameters based on the findings of this work and some of these parameters were thereafter used for the simulation of the base-case study with HTB2.



First: Construction files and user material library data were developed in order to populate HTB2 with data drawn from the literature and the stakeholders engagement

Second: In order to manipulate HTB2 files to include the impact of plants indoors, this module has been explored and trialled with data from literature to provide 'occupancy' figures that reflect the characteristics of plants within this simulation process.

Third: Information on the lighting requirements of vertical farms was gathered to be included in this module. The chosen lighting systems for this case study was LED-light. Data from vertical farming publications was used to populate this module.

Fourth: Ventilation is also a relevant module influencing vertical farms. This module currently includes the consideration of the behaviour of moisture content indoors. This framework suggests that a further parameter can be considered in more detailed here, for the purpose of vertical farms. This can potentially link condensation and dehumidification to water requirements of vertical farms (for Hydroponic systems, etc.)

Key: The green boxes represent the modules of HTB2 that were identified in this study as the most relevant for the design of vertical farms

Figure 25. Details on the chosen HTB2 modules to focus this framework.

As can be observed in Table 10, there are a number of gaps in the literature related to these relevant parameters. Therefore, some of the outcomes of the work described in this chapter aim to demonstrate how this framework can assist to fill some of these gaps.

Table 10. Parameters for simulation gathered from literature review, plus other relevant data within the context of vertical farming.

		Al-Chalabi (2015)	ZipGrow Towers (Appendix 01)	Wang et al. (2016)	Li et al (2016)	Chen et al. (2016)	Wang et al. (2016)	Graamans (2017)	Benis et al. (2017)	Tsitsimpelis (2016)	Graamans (2018)
Photo Period (PP) (hours/day)		18	-	16	16 (start at 08:00 ends at 00:00)	16 (start at 08:00 ends at 00:00)	12	16	13	16	16
Dark Period (DP) (hours/day)		6	-	8	8	-	12 (start at 21:00 ends at 09:00)	8	11	8	8
Temperature (°C)	PP	-	15 min 23 max	24	23	23	25 (23 min -27 max)	21	17 (min 12)	-	(heating setpoint) 24
	DP	-		20	20	19	20 (18 min - 22 max)	19	28 (max 32)	-	(cooling/ ventilation setpoint) 30
Relative Humidity (%RH)	PP	-	50 - 70	60	60	-	several measurements recorded during the experiment	73	60	-	65 min 90 max
	DP	-				-		82	90	-	65 min 90 max
CO2 Concentration (µ mol.mol*-1)	PP	-	-	400	400	300-500	kept always the same as outdoors: 498 (CO2 balance enrichment method: if indoor CO2 50 µ mol.mol*-1 fell below outdoors'	-	-	-	1200 (!)
	DP	-	-					-	-	-	
Type of Lights Germination (G) Post-Germination (GP)	G	High-pressure sodium (HPS) 600 W lamps assumed	LED lights specifically design for crops growth (light bars emitting 511 STU/hr - spectral (blade)	Fluorescent lamps (TL-D 36W Phillips)	LED (16 multichip Z-LED) the rated power for each chip is 3W	-	-	-	-	LED	-
	GP			LED light plates (DC supply)		-	-	-	-	15 kW (transformer units)	-
Irradiance (µ mol.m*-2.s*-1) or Photosynthetic photon (PPF)	PP	-	-	150	50	169	150	100 - 300	-	120	500 (!)
	DP	-	-	200	started at 70 (for 10 days), then at 120 (for 15 days)			400 - 600 (l)	-	210	
Controlled Environment (yes/no)		-	yes	yes	yes	yes	yes	yes	yes	yes	yes
Growth Medium		hydroponic	soil based (in towers)	hydroponic	hydroponic	hydroponic	hydroponic	hydroponic	hydroponic	hydroponic	hydroponic
Water Requirements		10.7 l/m2	-	-	-	-	-	-	-	-	-
Number of Days		-	-	30 days	15 days of germination 25 days after	14 of germination 24 days after	36 days	-	-	-	-
Wind speed or ACH		-	-	-	-	-	-	4000 m^3/h or approx. 200 vol exchanges/h (!)	-	enters at 10 m/s dispersed average of 1.7 m/s and exhaust at 7 m/s	-

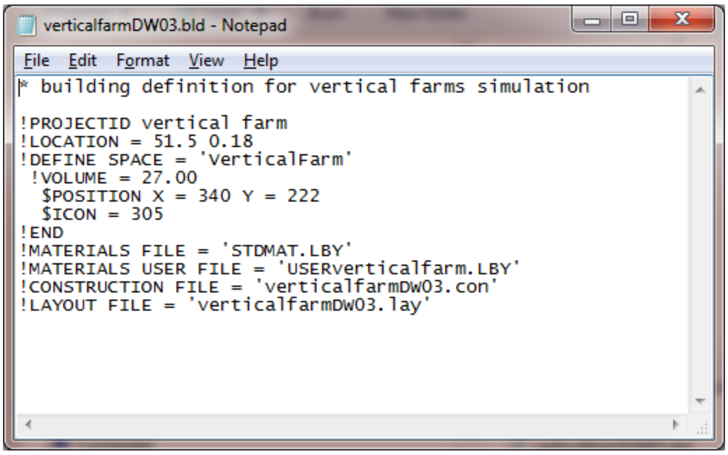
Table 10 (continued). Parameters for simulation gathered from literature review, plus other relevant data within the context of vertical farming.

	Al-Chalabi (2015)	ZipGrow Towers (Appendix 01)	Wang et al. (2016)	Li et al (2016)	Chen et al. (2016)	Wang et al. (2016)	Graamans (2017)	Benis et al. (2017)	Tsitsimpelis (2016)	Graamans (2018)
Systems	-	HVAC - only for cooling. Their plants and light generate enough heat to keep the system running successfully	-	-	-	air exchange and heat pump for cooling	HVAC for cooling and dehumidification	-	-	HVAC/Fancoil unit/Air cooled chiller
Light Utilization Efficiency (LUE) (g/kWh)	-	-	-	32 plants/m2/electric energy consumption	-	-	-		-	-
Renewables	Some information and estimation figures on the use of PV (or BIPV)	-	-	-	-	-	-	-	-	-
Certification		Modular farms are GAP (Good Agricultural Practice) certifiable			-		-	-	-	-
pH	-	5.5 - 6.5 (Lettuce)	-	6.3	-	6.0 to 6.5	-	-	-	-
Other Features	For water requirements, moody diagram equations were used to calculate the energy needed to pump the water in the building and to calculate the 10.7 l/m2 of water required	HEPA filters for air intake and exhaust systems. Commercial grade air conditioning and dehumidification		The Red/Blue ratio (R/B) has been considered. Only considered the electricity consumption of the illumination, i.e., cooling, ventilation and water pumping was ignored		This paper provides loads of details of sensor types and measuring equipment. Energy Consumption for heat pumps and air exchanger were measured by wattmeters and recorded every minute. Attempt to save electric energy by using the air exchanger.	VCD (Vapour Concentration Deficit)			

5.5.1.3 Detailed parameters: base-case study

This section will provide an example of how most of the identified relevant parameters for vertical farms can be integrated into this developed simulation framework, demonstrating how they are input in HTB2, using the base-case study as the first attempt.

Figure 26 shows a snapshot of the type of configuration files used by HTB2, where some basic information about the building is stated. This files are important due to the contains information such as geolocation coordinates as well as the volume and some other information necessary for the simulation engine to link this file with the rest of them.



```
* building definition for vertical farms simulation

!PROJECTID vertical farm
!LOCATION = 51.5 0.18
!DEFINE SPACE = 'VerticalFarm'
 !VOLUME = 27.00
  $POSITION X = 340 Y = 222
  $ICON = 305
!END
!MATERIALS FILE = 'STDMAT.LBY'
!MATERIALS USER FILE = 'USERverticalfarm.LBY'
!CONSTRUCTION FILE = 'verticalfarmDW03.con'
!LAYOUT FILE = 'verticalfarmDW03.lay'
```

Figure 26. HTB2 configuration file containing the initial basic characteristics of the building (BLD File).

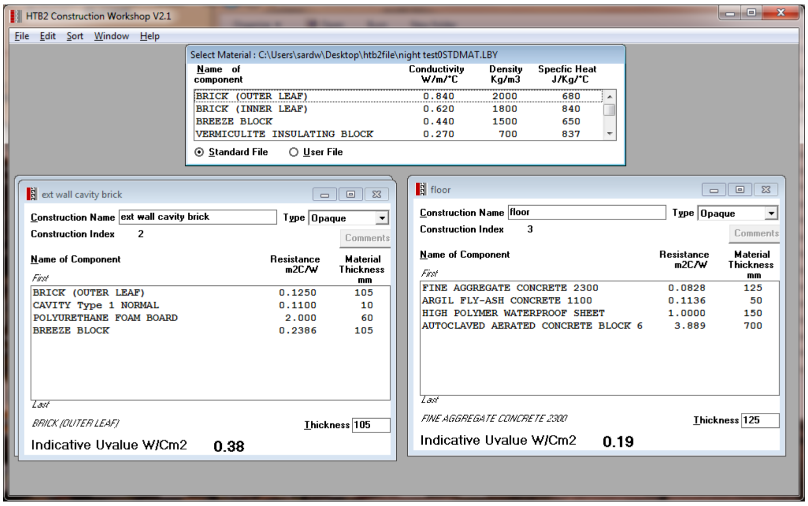
In addition, the parameters in Table 11 were used.

Table 11 – Simulation Parameters: Base-Case Study

Simulation Parameters: Base-Case Study		
Building Volume	27 m^3	
Temperature	Photoperiod	21 – 25 C
	Darkperiod	18 – 22 C
Lighting Hours	(i.e. Photoperiod)	16 hours (08:00 – 23:59)
Light Power	LEDs multi-chip	912 Watts (total)

The module of HTB2 handling the specific information about the building materials are the library and construction files. These modules are flexible enough to allow any vertical farming developer to tailor the materials and type of construction that are going to be used for any particular project. This investigation found that this kind of tool does not exist in the vertical farming community. The small sample of simulation attempts of vertical farms so far, have only used "black-box" type of software, making it difficult to have transparency of data and data-sharing, limiting the amount of potential collaborative work and comparison of parameters and testing results.

In these modules, relevant information regarding the thermal properties of building materials and their configuration is detailed. HTB2 allows users to build their own construction files and therefore have clear information about the u-values used and more (Figure 27). This information can easily be shared and compared.



Select Material : C:\Users\sardw\Desktop\htb2file\night test0STDMAT.LBY

Name of component	Conductivity W/m/°C	Density Kg/m3	Specfic Heat J/Kg/°C
BRICK (OUTER LEAF)	0.840	2000	680
BRICK (INNER LEAF)	0.620	1800	840
BREEZE BLOCK	0.440	1500	650
VERMICULITE INSULATING BLOCK	0.270	700	837

● Standard File ○ User File

Construction Name: ext wall cavity brick
Type: Opaque
Construction Index 2

Name of Component	Resistance m2C/W	Material Thickness mm
BRICK (OUTER LEAF)	0.1250	105
CAVITY Type 1 NORMAL	0.1100	10
POLYURETHANE FOAM BOARD	2.000	60
BREEZE BLOCK	0.2386	105

BRICK (OUTER LEAF)
Thickness 105
Indicative Uvalue W/Cm2 0.38

Construction Name: floor
Type: Opaque
Construction Index 3

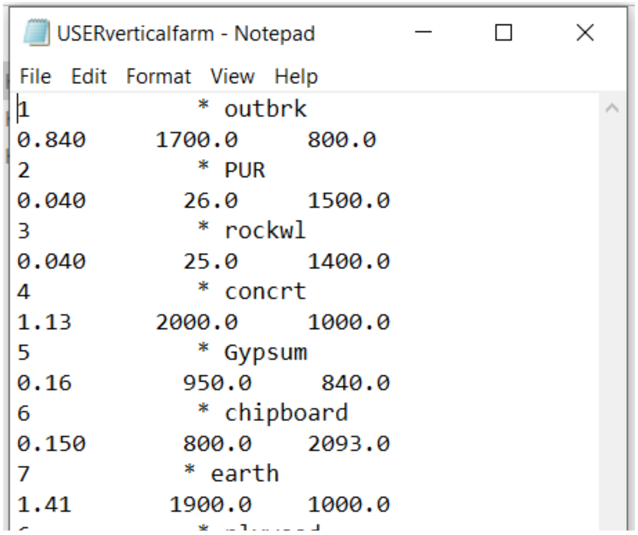
Name of Component	Resistance m2C/W	Material Thickness mm
FINE AGGREGATE CONCRETE 2300	0.0828	125
ARGIL FLY-ASH CONCRETE 1100	0.1136	50
HIGH POLYMER WATERPROOF SHEET	1.0000	150
AUTOCLAVED AERATED CONCRETE BLOCK 6	3.889	700

FINE AGGREGATE CONCRETE 2300
Thickness 125
Indicative Uvalue W/Cm2 0.19

Figure 27. Sample of construction files used for the various tests.

To achieve u-values calculations among others, HTB2 has a library of standard building materials with their thermal properties attached. In addition, there is also a "user library" of materials which can be designed for any context. As part of this framework, a specific library of materials for vertical farms was developed (see Figure 28). Nevertheless, very little information was found in the published literature specific to vertical farms. Some information on this topic is partially mentioned by Cattarin et al.

(2016) Benis et al. (2017b) and Graamans et al. (2018), where small details about the construction material of the wall of the building has been mentioned, but this was not clear or specific enough to even provide a u-value, i.e. mentioned a type of insulation but not u-value seemed to be included in their specific calculations. An important aspect of this section of the software tool is that the users of the framework can provide their own bespoke information related to the fabric of the building, feeding into the u-value calculator any particular arrangement of materials and thicknesses, having the capability to test and experiment different arrangements in this virtual setting. Hence, users are not restricted to specific material/thickness combinations. Exploration in this area, related to the most efficient combination of building fabric to interact with the specific characteristics required for a productive indoor environment for different types of crops or plants species, represent a valuable opportunity for further multidisciplinary collaboration in this area. Further details are provided in the appendices with regards to the data used in the simulations of this investigation, related to building materials and their properties, within HTB2. Figure 28 provides a sample snapshot of the type of layout used in the HTB2 files containing the information required in the library of materials. Note that the details required for the materials to be used in HTB2 are conductivity (W/m/C), density (kg/m3) and specific heat capacity (J/kg/C).



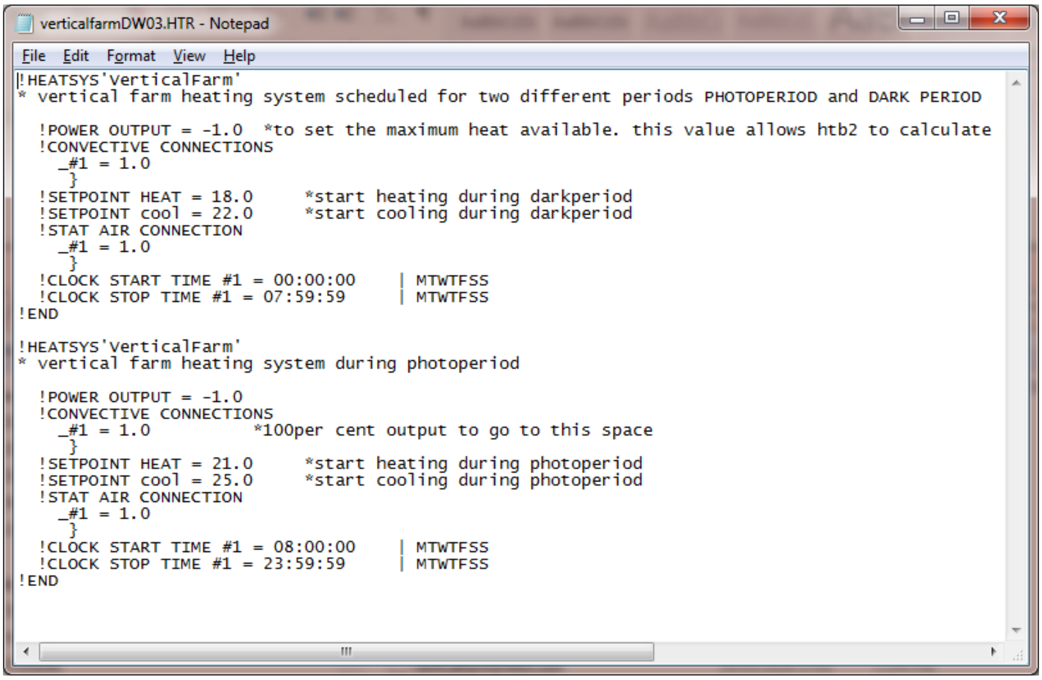
```
1             * outbrk
0.840     1700.0     800.0
2             * PUR
0.040       26.0     1500.0
3             * rockwl
0.040       25.0     1400.0
4             * concrt
1.13      2000.0     1000.0
5             * Gypsum
0.16       950.0      840.0
6             * chipboard
0.150      800.0     2093.0
7            * earth
1.41       1900.0     1000.0
```

Figure 28. User library file for vertical farm. For each material added to the library three main values are provided: conductivity (W/m/C), density (kg/m^3) and specific heat capacity (J/kg/C).

Services:

- Heating:

To simulate vertical farms more reliably, two main sets of requirements must be fulfilled: for photoperiod (PP) and for dark period (DP) (see Table 10). Figure 29 below shows the heating file specifying the requirements for both different periods of this case-study. Figure 29 shows that the ranges of optimum temperature specified here are: 18C to 22C for 'dark period' and 21C to 25C for 'photoperiod'. These values are taken from literature and stakeholder engagement, gathered and included in Table 10. The type of heating system specified for this case study was a basic convective heating system.



```
!HEATSYS'VerticalFarm'
* vertical farm heating system scheduled for two different periods PHOTOPERIOD and DARK PERIOD

  !POWER OUTPUT = -1.0  *to set the maximum heat available. this value allows htb2 to calculate
  !CONVECTIVE CONNECTIONS
    _#1 = 1.0
     }
  !SETPOINT HEAT = 18.0     *start heating during darkperiod
  !SETPOINT cool = 22.0     *start cooling during darkperiod
  !STAT AIR CONNECTION
    _#1 = 1.0
     }
  !CLOCK START TIME #1 = 00:00:00    | MTWTFSS
  !CLOCK STOP TIME #1 = 07:59:59     | MTWTFSS
!END

!HEATSYS'VerticalFarm'
* vertical farm heating system during photoperiod

  !POWER OUTPUT = -1.0
  !CONVECTIVE CONNECTIONS
    _#1 = 1.0          *100per cent output to go to this space
     }
  !SETPOINT HEAT = 21.0     *start heating during photoperiod
  !SETPOINT cool = 25.0     *start cooling during photoperiod
  !STAT AIR CONNECTION
    _#1 = 1.0
     }
  !CLOCK START TIME #1 = 08:00:00    | MTWTFSS
  !CLOCK STOP TIME #1 = 23:59:59     | MTWTFSS
!END
```

Figure 29. Heating file base-case study

In this particular case, the heating file is giving instructions to turn the heating on and off at the specific temperatures' thresholds. Based on the data gathered and averaged to choose the most representative parameters found in literature, it has been found that a common practice is to have two specific functioning periods:

1. During the photoperiod: Lights to be turned on typically 16 hours a day (but it will vary according to the type of plant, etc. This can be easily changed by the user)
2. During the dark period: Lights are off 8 hours a day.

- <u>Lighting power:</u>

This file contains the information of the capacity of the specific arrangement of lights inside the vertical farms. In order to calculate the specific lighting for the case study, information found in literature was used as the main reference for this exercise.

There are a number of different lights that can be used for vertical farms. It has been found that LED lights are the most efficient (Mitchell and Sheibani 2015; Higgins 2016; Gupta and Ganapuram 2019) and therefore these lights were the ones used for this simulation study. Considering that the base-case study has 2 towers of planting trays (Figure 21), each with 4 levels, the most approximate lighting arrangement for them is detailed in Figure 30 below. The specific distance measurements were taken from the reference (Li et al. 2016).

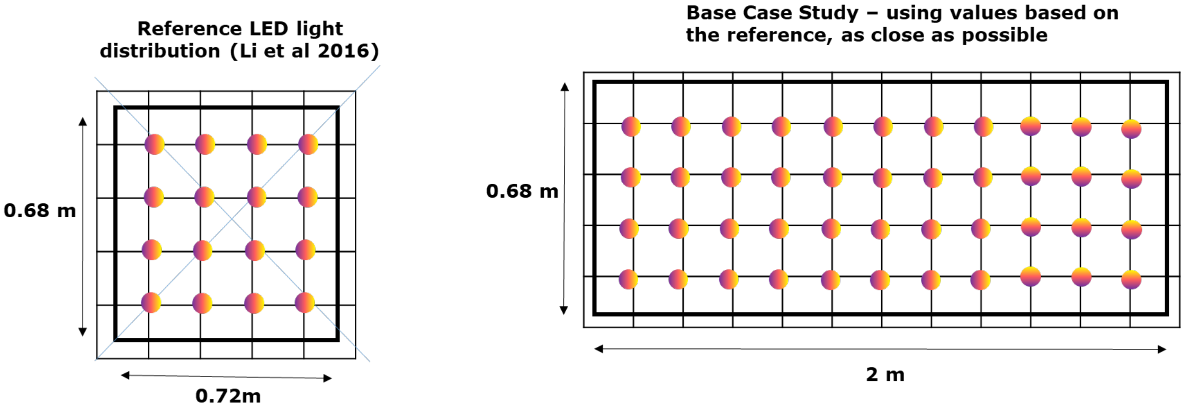
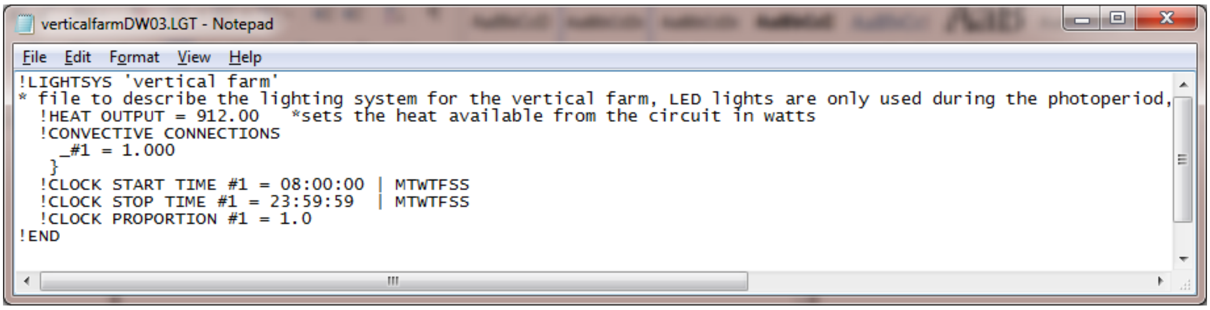


Figure 30. Lighting arrangement

Based on detailed information published by (Li et al. 2016) this multi-chip LEDs illumination system contains an array of 3W chips (rated power for each chip). Calculating that the total growing area is 9.6 square meters (i.e. the size of each grow tray is 2m x 0.6m = 1.2, and there is a total of 8 trays = 9.6 m2 grow capacity). The lighting arrangement suggested by Li et al. (2016) shown in Figure 30 allows therefore for a total of 304 LED chips for this specific area, hence 304 x 3 Watts = 912 Watts. This final figure is the number required for the lighting file of HTB2 (Figure 31). The lights are only on during the photoperiod 16 hours a day, from 08:00 until 23:59. All this information is stored in this HTB2 module.

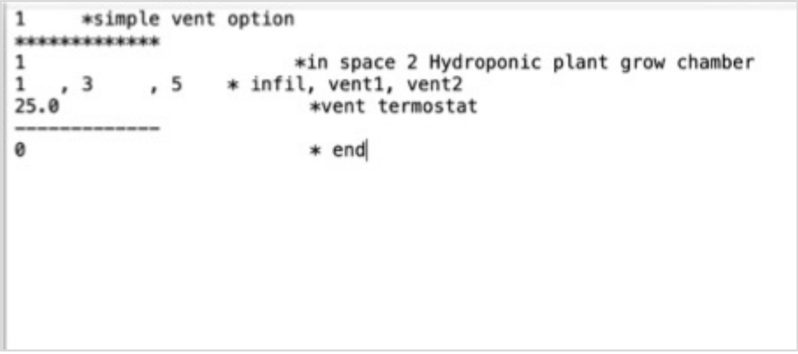


```
!LIGHTSYS 'vertical farm'
* file to describe the lighting system for the vertical farm, LED lights are only used during the photoperiod,
  !HEAT OUTPUT = 912.00   *sets the heat available from the circuit in watts
  !CONVECTIVE CONNECTIONS
    _#1 = 1.000
   }
  !CLOCK START TIME #1 = 08:00:00 | MTWTFSS
  !CLOCK STOP TIME #1 = 23:59:59  | MTWTFSS
  !CLOCK PROPORTION #1 = 1.0
!END
```

Figure 31. Lighting file base-case study

- Ventilation file:

Figure 32 below shows an example of a ventilation file for HTB2, different air changes per hour can be specified here for any scenario. The published evidence of vertical farms is not clear about what are the recommend ventilation rates for vertical farms. This will of course vary from case to case, but the fact that there is not clear published data for almost any case study is a significant gap identified and hopefully tackled by the use of this framework.



```
1     *simple vent option
*************
1                        *in space 2 Hydroponic plant grow chamber
1   , 3     , 5    * infil, vent1, vent2
25.0                       *vent termostat
-------------
0                          * end
```

Figure 32. Ventilation file base-case study

- Occupancy file:

It is anticipated that the main “users” of this building will be the plants. Of course, there will be circumstances where occasionally there will be a person entering the building to look after the plants, but in this case study, this has been considered as negligible. This is due to the length of time a person remains in the building, compared to the duration of the plants inhabiting the space. Nevertheless, in future replications of this simulation method, the presence of human beings can be considered within the simulations, if this is an item considered as significant, i.e., in the cases of larger vertical farms, where there might be a more frequent interaction between human beings and plants. This kind of cases can also be considered into this simulation, however, for this original pilot studies this has not been consider yet, mainly to avoid unnecessary complexity to the schedules at this point.

Henceforth, in this case, the "users" of the building in this simulation are the plants. HTB2 considers the users, or occupants, of the buildings as sources of heat and moisture (Alexander 2008). In other words, the module related to occupancy only requires the values related to potential heat and humidity gains resulting from the "occupants". The key input data required for this occupancy module are: heat output (in Watts), water vapour (in grams per second) and "number of occupants". The other numbers found in the data file of this modules are just related to the schedule which in this case, it has been set to be always occupied (seven days a week, 24 hours a day). This of course can be changed to the individual needs of different cases.

In order to be able to adapt this occupancy module to fill all the needs for a more accurate simulation of a vertical farm, there are two options:

1. Work with a computer programmer to change the original code of the software (the programming language of the source code is Fortan) to make this module, and potentially other modules of HTB2, more receptive to the characteristics of plants. This occurs because this software was not originally written for vertical farms, but to use physics and mathematical formulas to analyse the behaviour of regular buildings. This option is perfectly feasible, within a larger project, where a team of experts can be brought into this project to improve the software tool, since HTB2 has an open-source code. But this falls outside the boundaries of this PhD.
2. "Trick" the software into thinking that the occupants are "people" instead of "plants". After all, it does not matter to HTB2 if the occupants are people or plants (or other!). All the software tool is doing is arranging data/numbers to fit into the formulas and calculations running in the background of the software, the code.

Therefore, to overcome the current limitations of the software, the author of this thesis searched for the best way to achieve option 2 above: "trick" the software, to be able to input the characteristics of the plants instead of people. To pursue this route, the HTB2 manual and all support documents were scrutinised, to find clues on how to input the necessary data, in a way that the software would understand and take into consideration in the most accurate manner, for the context of the vertical farm. Overall, this module had to be manipulated to reflect the moisture content released by the plants, as closed as possible to the reality. Also, ensuring that any heat outputs that the software tool attempts to attach to occupants are avoided, since this could interfere significantly with the calculations, since plants and humans release and absorb heat in a different manner: humans are exothermic (heat-producers), whilst plants are predominantly endothermic (heat-consumers) (Wohl and James 1942).

To be able to develop the right simulation tool to consider all the complexities behind the differences between the behaviour of plants compared to humans, falls beyond the scope of this study. As mentioned above, this is one of the main recommendations for further research work. It is clear that this software tool has the capability to include further formulas into its calculations, but in order to develop this intricate feature, a team of experts must be added to this task: a plant scientist, a mathematicians or physicist to develop the necessary formulae and a computer programmer to alter the software tool).

However, to work around the current limitations of the software, the best way to tackle this issue has been to disable the heat gains from the "occupants". In other words, the heat output from "occupants" for this simulation framework has been set to zero (0 Watts). By doing this, the software understand that there is a source of water vapour output from the "occupants" but not heating. Finally, to input approximate values of water vapour output (in grams per second, or gr/s, as needed by HTB2 code) and the "number of occupants" the following comparative calculations between plants and humans have been undertaken:

Based on the literature (Tenwolde and Pilon 2007), water vapour released from plants varies across different types and environments. Similarly, people also released different levels of water vapour, but for the purpose of this comparative analysis two **average water vapour values** published by Tenwolde and Pilon (2007) were selected for both:

(1) One plant can release approximately 2.5 grams per hour (g/h) and

(2) One person can release approximately: 300 grams per hour (g/h)

These values were compared to calculate equivalent figures and then converted to the units required by HTB2 (grams per second, g/s). Simple mathematical calculations were used to achieve the approximate suitable values to input:

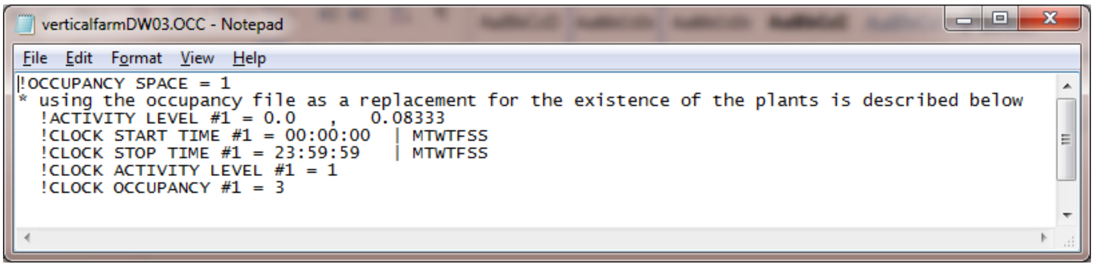
- 300 / 2.5 = 120 i.e. 120 plants could produce an approximate amount of water vapour equivalent to 1 person.
- The estimated number of plants within the vertical farm has to be calculated based on the size and quantity of growing trays (place where plants are cultivated).
- In the base case study there are 8 growing trays. Each tray has enough space to grow approximately 36 plants (estimated calculations made based on the physical dimensions of the vertical farm, Figure 21). This figure will vary significantly depending on the size of the plants. The total number of plants in this vertical farm therefore are: 8 x 36 = 288 plants
- If 288 (plants) is divided by 120 plants (calculated in the first bullet point above), the resulting number will provide an estimated equivalent number of people required to produce a similar amount of water vapour. 228 / 120 = 2.4 people. This has been approximated to 3 people.
- Finally, since HTB2 is working with the assumption that the occupants are people, the water vapour rate produced per person had to be included also. Using the same literature reference:
  300 g/h / 3600second = 0.08333 g/s
  This is the water vapour figure also used for this simulation.

In summary, the calculations above resulted in the following values that would be used as the key inputs for the required by HTB2's occupancy file of this base-case study:

- Heat output (in Watts): **0 W**
- Water vapour (in grams per second): **0.08333 g/s**

- Number of occupants: **3 people** (which is the equivalent of the 288 plants that are estimated to occupy the vertical farm)

These values can be seen in Figure 33.



```
!OCCUPANCY SPACE = 1
* using the occupancy file as a replacement for the existence of the plants is described below
  !ACTIVITY LEVEL #1 = 0.0    ,    0.08333
  !CLOCK START TIME #1 = 00:00:00   | MTWTFSS
  !CLOCK STOP TIME #1 = 23:59:59    | MTWTFSS
  !CLOCK ACTIVITY LEVEL #1 = 1
  !CLOCK OCCUPANCY #1 = 3
```

Figure 33. Occupant/plants file of the base-case study

- <u>Weather file</u>

Similarly, the weather files are a simple straightforward process of obtaining the desired weather file of the given location. In this case, weather data from EnergyPLus is transferred to HTB2 to perform the simulation.

5.5.2 Simulations results and discussion.

One of the key focus of this investigation is to assess how the outcomes from HTB2 can be used to model and compare some key parameters of vertical farms. The flexibility of HTB2 allows various modules of parameters to be integrated in the simulation process. Therefore, the development of this simulation framework, mainly focuses on the modules of HTB2 that are most relevant for vertical farms. A number of trials were therefore designed in order to test the specific parameters.

<u>Trial 1:</u> Testing results based on ventilation rates.

An important parameter to improve the efficiency of vertical farms is to ensure that the necessary ventilation can be achieved to provide the adequate environment for plants to thrive (Wang et al. 2016; Graamans et al. 2018). Mathematical models exist that can help to calculate the levels of CO2 necessary for different plants to grow. They have been tested for greenhouses (Vanthoor et al. 2011a; Vanthoor et al. 2011b) and some initial attempts to integrate the models used in greenhouses have been tentatively referenced by researchers in areas related to vertical farms (Benis et al. 2017b; Graamans et al. 2018). Nevertheless, very little evidence has been published on the impact of different rates of ventilation in vertical farms and this evidence is unclear: one author publishing the results of an underground monitored farms to require as little air changes per hour as possible to maintain the CO_2 at the optimum level, they argue they need less than 3.5 air changes per hours (Jans-Singh et al. 2019). On the other hand, in a different publication focused on results from a trial simulation study of a high-tech vertical farm, the study suggests that in order to provide an optimum air mixing and uniform condition across the farm, it required "200 volume exchanges per hour".

Evidently, the level of ventilation in a vertical farm is important, but there is not enough transparency and evidence in this area of research. Ventilation helps to regulate the optimum temperature and humidity levels in vertical farms. These parameters have "acute impact on plant growth and morphology […] and plant transpiration" (Tsitsimpelis et al. 2016). Therefore, they affect the healthy growth of plants and hence final produce. This investigation considered that the lack of information in this area is a significant gap that can be tackled with this framework to some extent. This method therefore encourages experts in the field of indoor farming to explore the module of HTB2 which can be used to shed light on the impact of the ventilation rate at an early design-stage for any prospective vertical farm project. This module can also be manipulated in the future to include further aspects that are affected by ventilation, i.e., CO2, plants transpiration, latent energy flux of plants, etc.

The results obtained from this initial interrogation, using the base-case study as an example, can be seen in Figures 34 and 35. These graphs present the interaction between the indoor air temperature and relative humidity (RH), also compared to the outside weather. As it can be observed in the results (Figure 34 and Figure 35), despite the fact that the building is fully sealed, insulated and there are no windows in this project, the outside conditions have a noticeable impact on the indoor climate. Observations drawn from Figure 34 and Figure 35 evidence the significant influence of the rate of air changes per hours (ACH) on the indoor air conditions. This exercise has been included in this investigation, due to the fact that this is an important gap in the literature of vertical farms (Table 10). The lack of published evidence in the area of ventilation is highlighted by the several gaps within the table. The results obtained from this simulation show that the systems providing 10ACH are able to deliver the desired temperature more accurately than 5ACH. Note that there are some hours during the summer months, that both scenarios overheat (results are above the set optimum parameters: T_{max}=25°C and T_{min}= 21°C), and the overheating issue is more prevalent in the 5ACH scenario than the 10ACH.

The lower temperature levels achieved with the higher ventilation rate is not a surprising result. The levels of humidity however seem to be better regulated by the 5ACH system. Figure 35 shows a significantly higher level of relative humidity despite of the higher air changes per hour. This could be due to the low temperatures and conflicts with the air dew point or other parameters. This is an example of the importance of performing a holistic exploration, since all these parameters affect each other and thereafter also the plants. Furthermore, considering that the CO2 levels will also play an important role on the relationship with ventilation, i.e. fewer ACH help to maintain better levels of CO2 (Jans-Singh et al. 2019), then careful consideration of all the necessary parameters needs to be implemented at the design stage of vertical farms. These investigations play a significant role in finding the "sweet point" when balancing all these parameters, and this is extremely important also because different crops required different specifications. Hence, by having a standardise method to follow the investigative process, vertical farms can be planned for optimum indoor environment despite of the different scenarios.

Based on the findings from this study, it is recommended to have a holistic approach - the information obtained from this framework can be coupled up with other models in the future that also take into consideration further parameters (Benis et al. 2017b; Graamans et al. 2020), as well as examples of monitored case studies of active vertical farms (Jans-Singh et al. 2019).

In conclusion, by assessing these parameters presented in this initial study, it was found that further information on this area will potentially benefit the vertical farming community to understand and approach the ventilation strategy of vertical farms from a different perspective. In further developments, this part of the framework can be linked to communicate with further parameters that also interact with ventilation (i.e. CO2, plants transpiration or latent energy flux of plants). This can be particularly valuable to set as a standard calculating process since different crops will have different requirements. Therefore the more automation that can be achieved in this process (Shamshiri et al. 2018) to achieve more transparency of data and ease of sharing, will highly benefit this community.

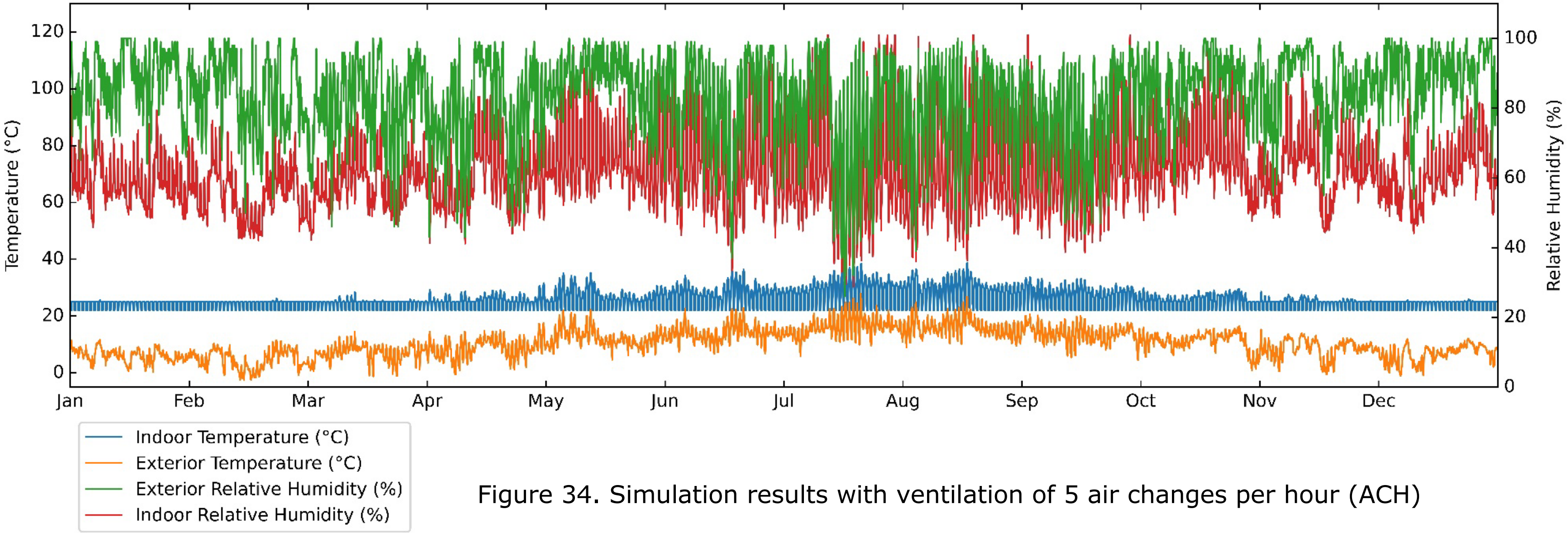


Figure 34. Simulation results with ventilation of 5 air changes per hour (ACH)

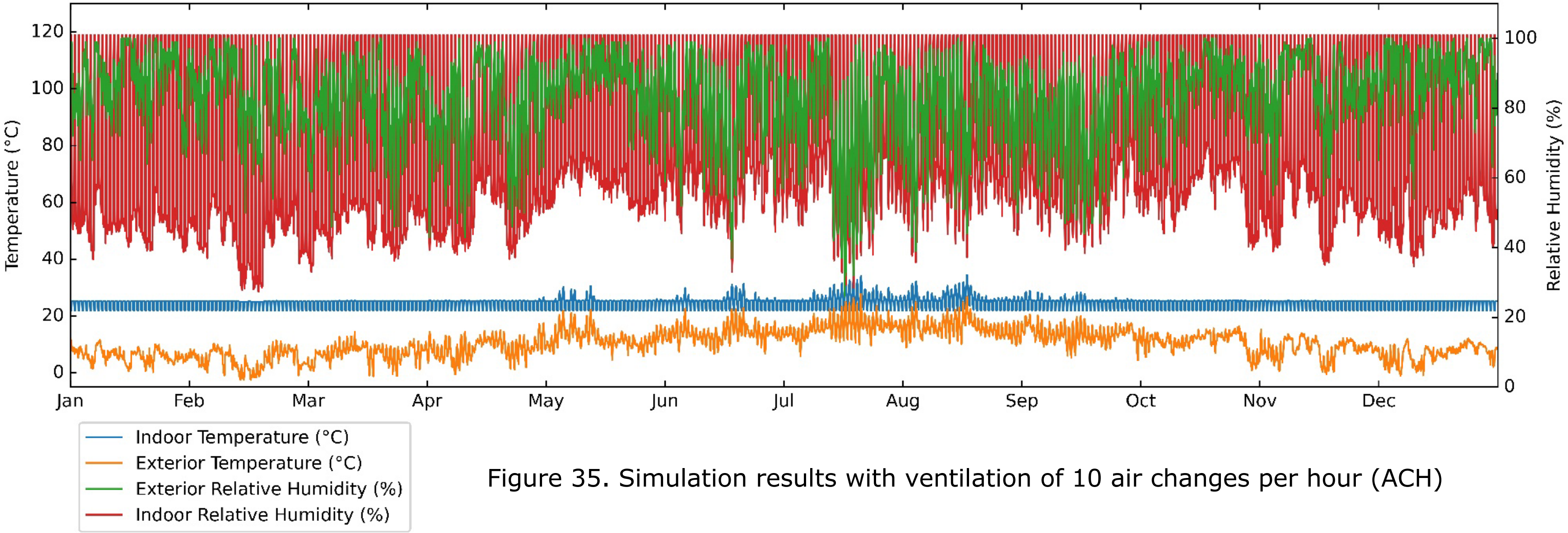


Figure 35. Simulation results with ventilation of 10 air changes per hour (ACH)

Trial 2: Seasonal Results.

Seasonal variability of indoor air temperature and humidity is a relevant factor to ensure optimum indoor conditions all year round (Tenwolde and Pilon 2007; Broyles 2008). Nevertheless, this is a topic that has been untapped by the vertical farming research community due to routine assumption that indoor farming does not get affected by the outside weather (Kozai et al. 2016b; Al-Kodmany 2018). By using the tool in this framework analysis, this suggestion has been rebutted as can be observed in the data presented in Figures 36 to 43, with specific information of the seasonal variability of the indoor conditions of vertical farms.

The results in Figures 36 to 43 correspond to the simulation using the 5ACH ventilation parameter. From the results, it can be inferred that the average indoor temperature was kept at the desired level in this simulation trial. The current environmental controls used in this case study, managed to keep the monthly average temperature within the desired range, for the optimum development of plants. The humidity was significantly more fluctuating, but maintained the desired optimum range, i.e., approximately between 70% to 90% (Benis et al. 2017b; Graamans et al. 2017). Interestingly, this behaviour closely reflects also the behaviour of the outside temperature, which begs the question of integrating further parameters and expert knowledge into a decision to assess the need of mechanical ventilation or looking into alternative ways to integrate more environmentally friendly methods to achieve the necessary parameters, such as the ones suggested by Benis and Ferrão (2018) to optimise efficiency by exploring potential fields of improvement such as thermal insulation (which can be easily integrated into this design framework and in active vertical farms) or by natural ventilation (Benis and Ferrão 2018, pp33). This study will go one step further and recommend that this optimisation process investigate the seasonal variability of these parameters (as seen in Figure 34 to Figure 43) to assess if natural ventilation is not viable all year round. Then, evidence can be established by setting up the case study scenario and obtain data to support which seasons might be suitable for natural ventilation and propose a mechanical ventilation system with bypass for the expected seasons where natural ventilation can be utilised.

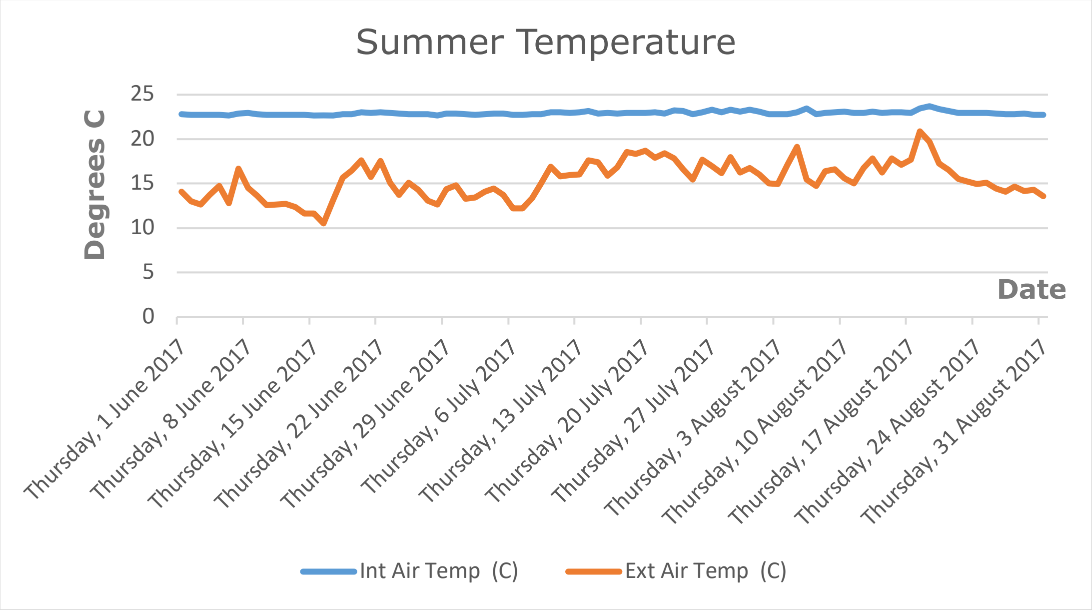


Figure 36. Summer temperatures interactions:
Indoors and Outdoors (Base-Case Study)

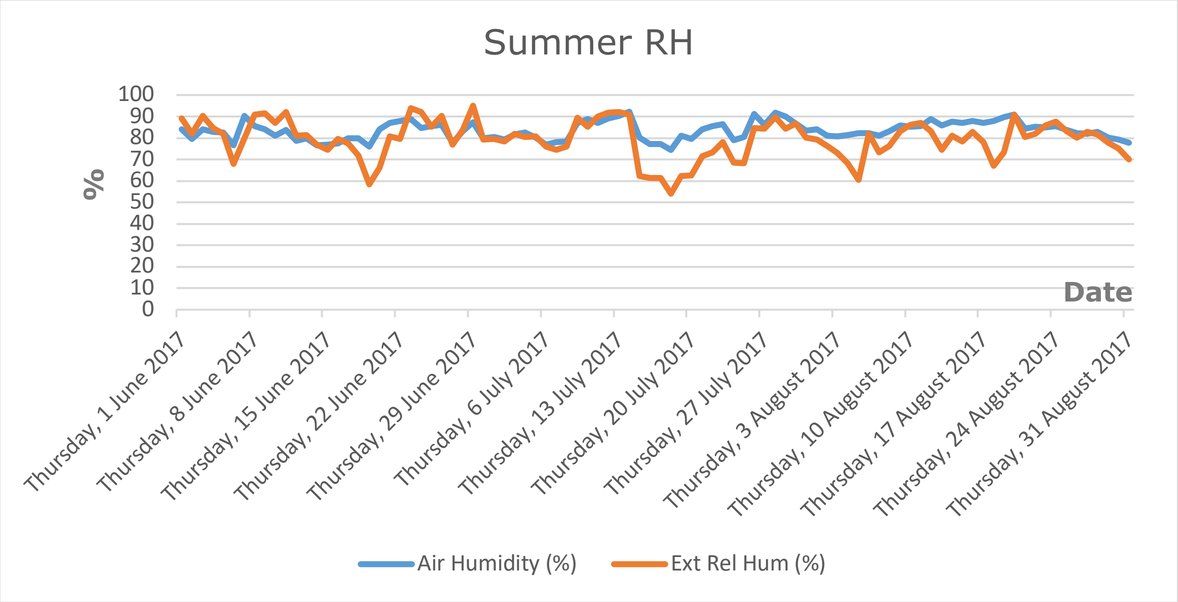


Figure 37. Summer Relative Humidity interactions:
Indoors and Outdoors (Base-Case Study)

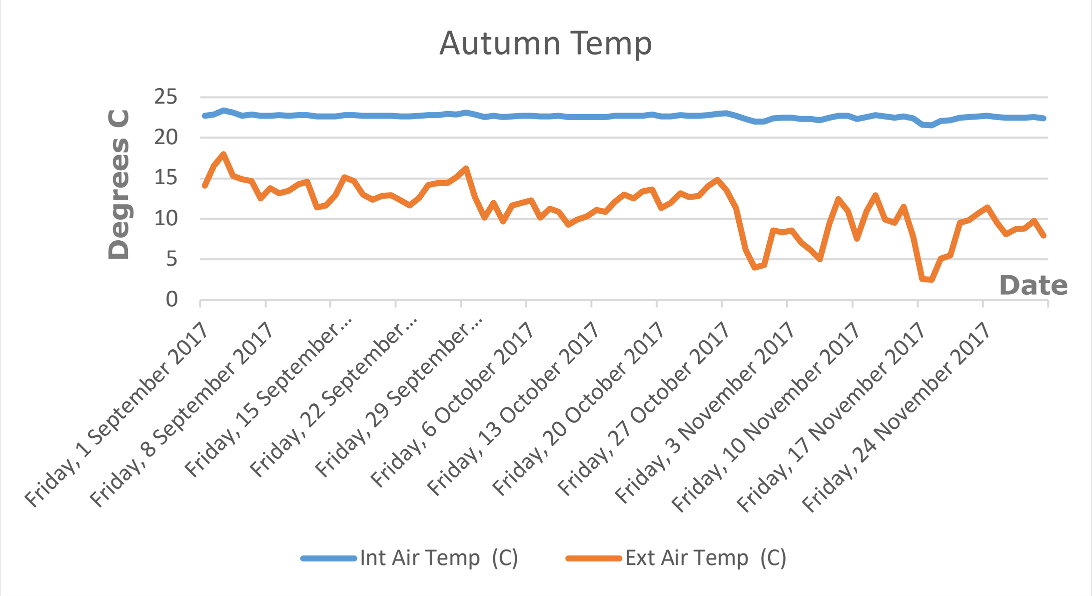


Figure 38. Autumn temperatures interactions:
Indoors and Outdoors (Base-Case Study)

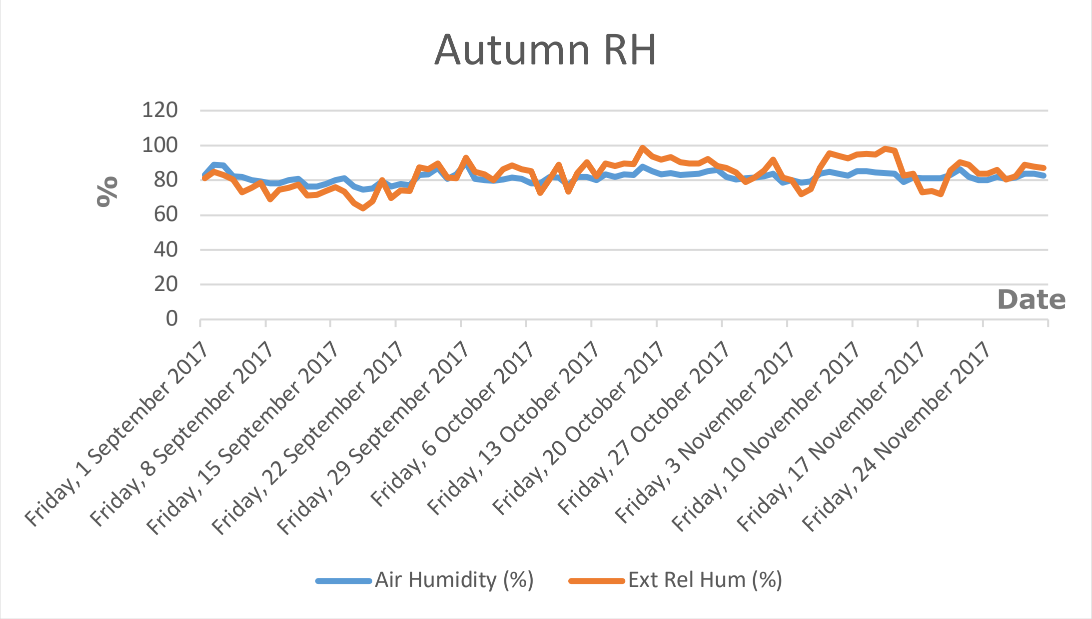


Figure 39. Autumn Relative Humidity interactions:
Indoors and Outdoors (Base-Case Study)

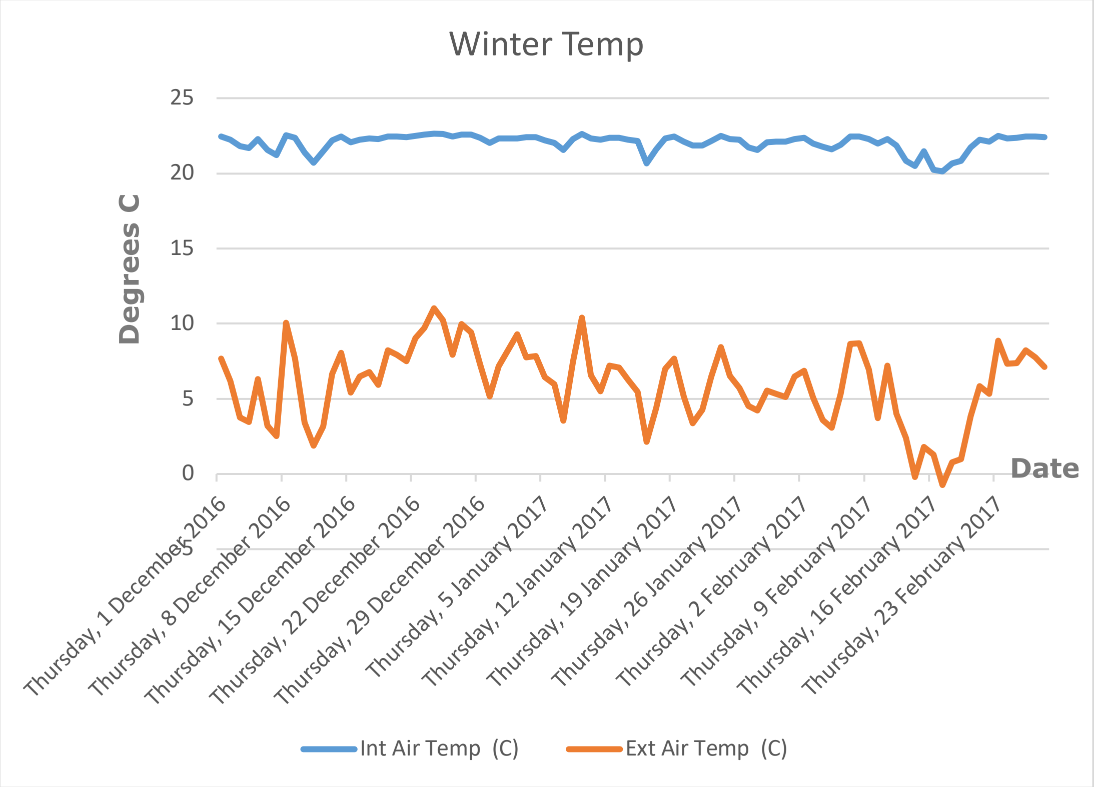


Figure 40. Winter temperatures interactions:
Indoors and Outdoors (Base-Case Study)

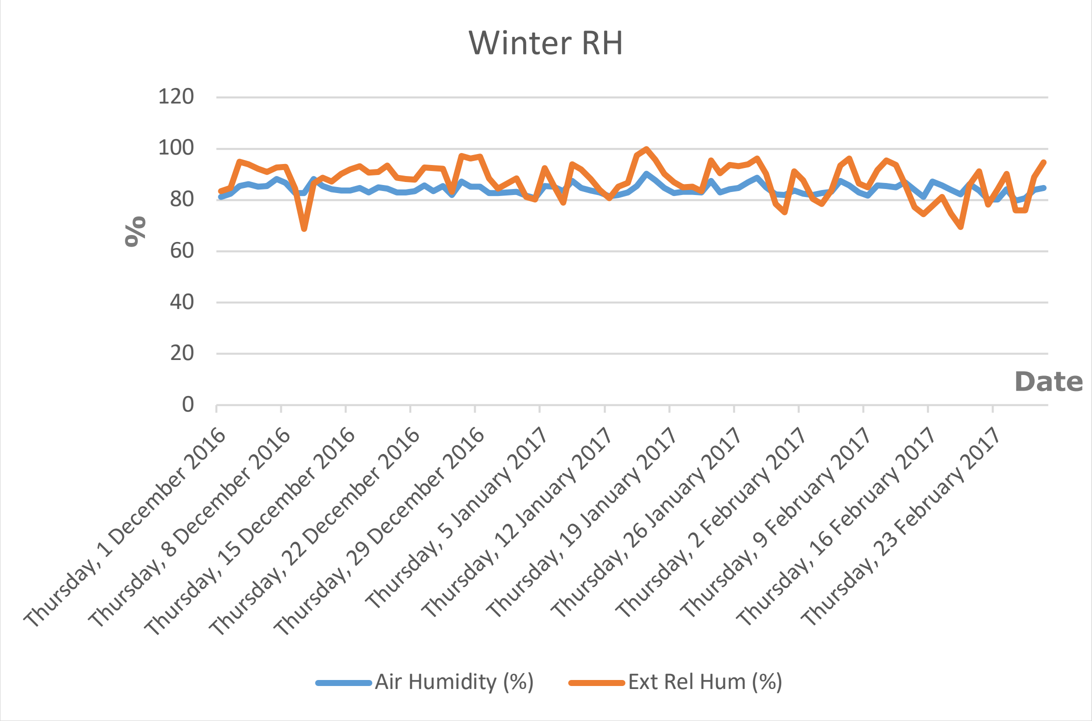


Figure 41. Winter Relative Humidity interactions:
Indoors and Outdoors (Base-Case Study)

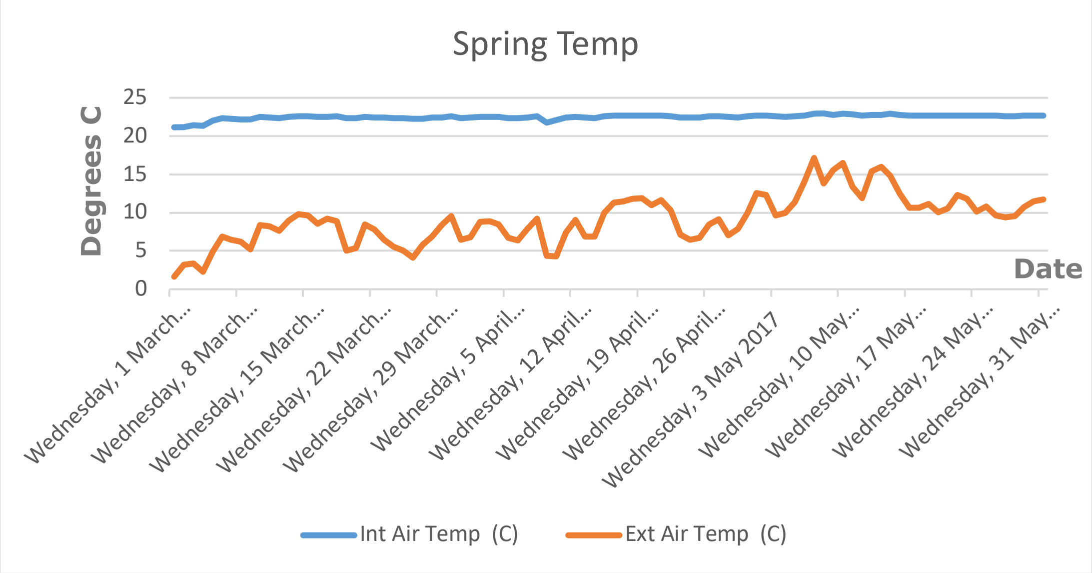


Figure 42. Spring temperatures interactions:
Indoors and Outdoors (Base-Case Study)

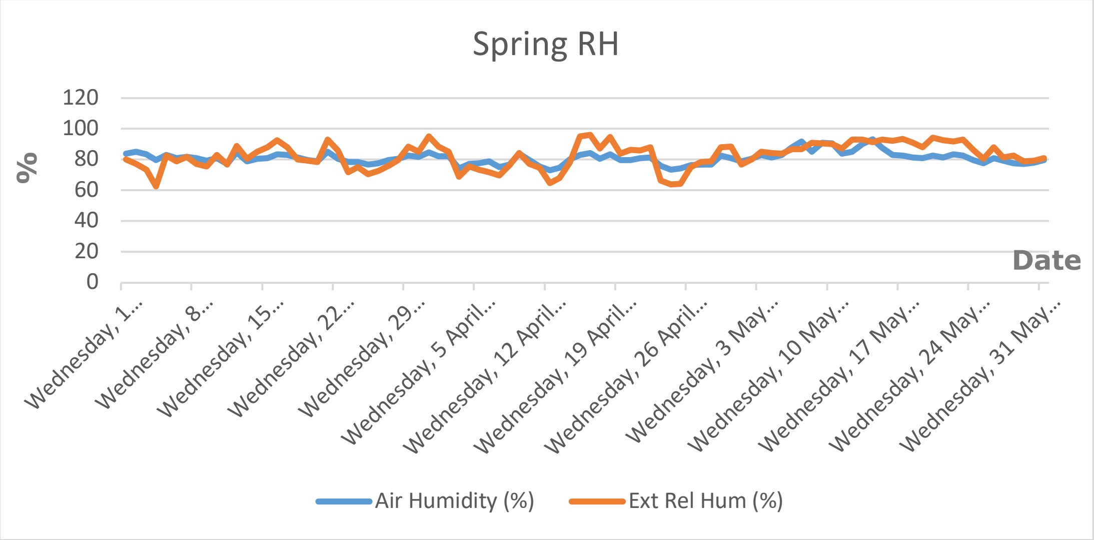


Figure 43. Spring Relative Humidity interactions:
Indoors and Outdoors (Base-Case Study)

Trial 3: Typical week queries.

Similar to the above trial, no detailed information is usually available for vertical farms to gain insight evidence with as much detail as a typical week. This is a characteristic that can be exploited by using HTB2 as the assisting tool for this framework. HTB2 can provide simulated data with resolution of an hour, and it builds up to provide data for any length of time, adding up to yearly data. The data can be selected to show particular parameters relevant to the analysis of vertical farms. For example, detailed data on energy consumption, related to lighting, air conditioning, moisture, ventilation, heating, etc. Details can be obtained for different scenarios to create comparative databases relevant to particular crop types, for example. The aim is to be able to assess best alternatives to achieve optimum indoor environment for any crops.

Based on the detailed data obtained with the results from the simulation with HTB2, weekly detailed graphs were created, initially using the hourly data. Figure 44 and Figure 45 show examples of how this data can be presented. In future development of this framework, it is recommended to use this as a tool to integrate various other parameters influencing each other, in order to achieve holistic results at this phase of the analysis. This weekly assessment was developed as part of this study, as an interesting feature of this methodology, particularly due to the short turnaround time of some crops typically produced in vertical farms. For example, some microgreens, depending on the type of crop and growing conditions, can grow as fast as 7 days, from germination to harvest (Chen et al. 2016; Li et al. 2016; Wang et al. 2016). Therefore, a weekly analysis can provide valuable insights to identify which crops to grow which weeks of the year where less energy could be required to achieve the specific optimum conditions.

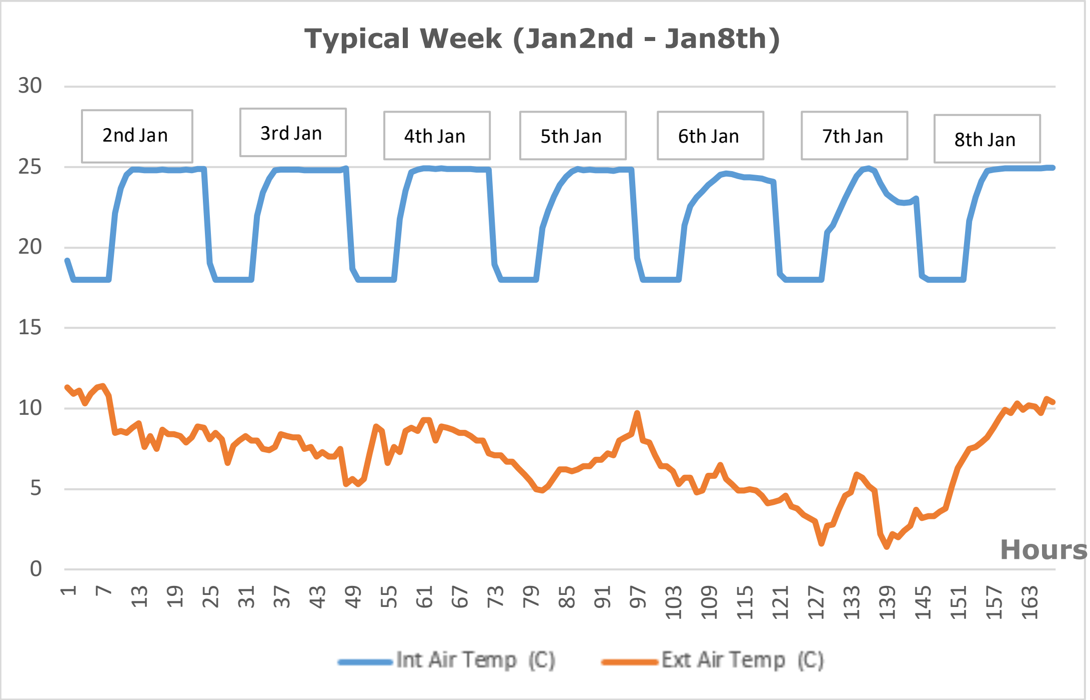


Figure 44. Sample of a weekly data analysis for a typical winter week. Hourly data

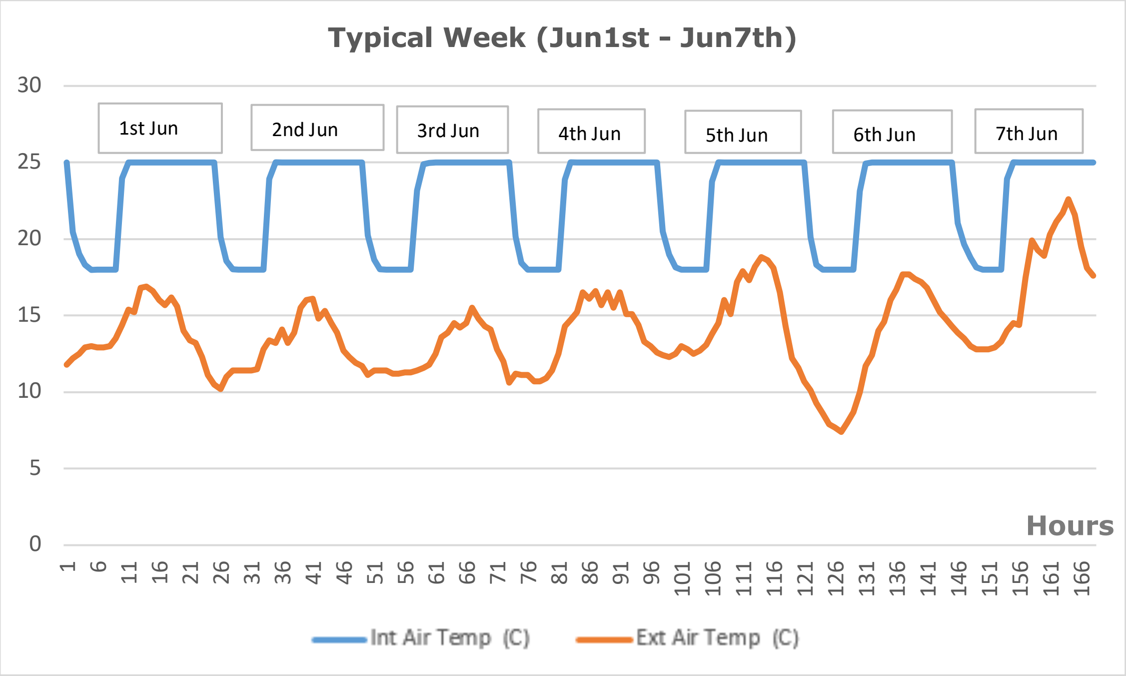


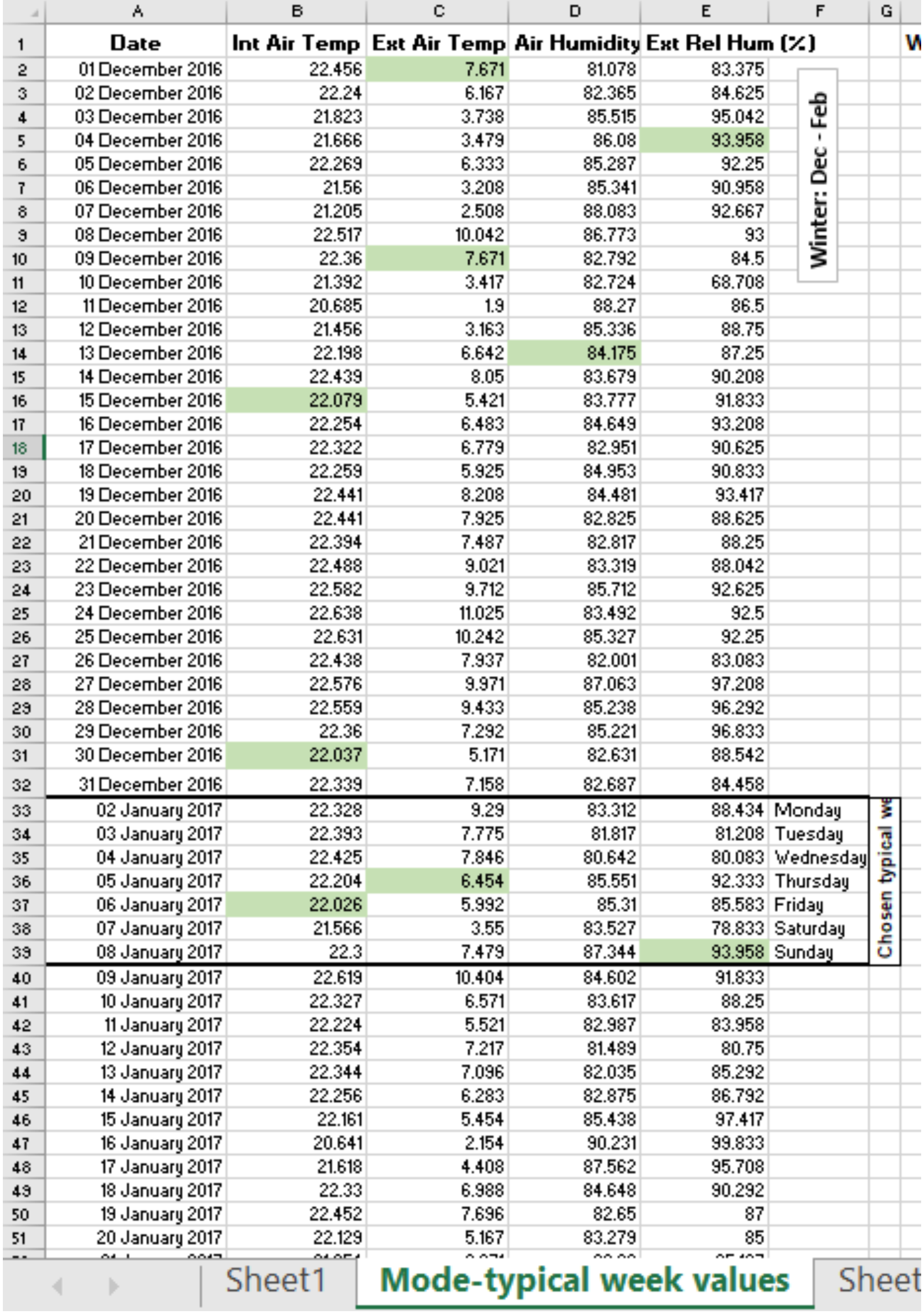
Figure 45. Sample of a weekly data analysis for a typical summer week. Hourly data

Building up on this data, Table 12 shows a snapshot of a sample arrangement of the data for the next level up of the data, where the hourly values were used to provide daily averaged data and exported and sorted into a table highlighting the particular parameters that are being investigated for a particular scenario. By sorting the data in this manner, better understanding of the seasonal variability of the data can be identified. The focus on this case were the extreme seasons, i.e. winter and summer (to gauge the behaviour of the vertical farm under cold and hot external conditions). With the help of basic statistical assessment of average values of the data, the information within this table was used to select a typical week for each of these two main seasons (winter and summer).

Table 13 shows the descriptive statistics that were used to select the data for the most representative characteristics, for one week for each season under analysis. To select a typical week for the two seasons, all the daily averages of a whole season were scrutinised. Values were classified using the standard deviation (SD), as well as the mode, median or mean (average) where appropriate. Based on this analysis, the most representative figures were highlighted in green on the table with all the daily averages for each of the seasons, Table 12 shows a snapshot of the table for the winter season. (see Table 14). To choose the particular values that were the most representative for each parameter, the first step was to calculate the SD for each of them (see Table 13). A low standard deviation (SD) means the values of the data are clustered around the mean (or average). Therefore, for the Internal Air Temperature (C) the selected representative values have been chosen to be the closest to the "mean" of the data (or the average), see chosen values in red in Table 13. However, for the other characteristics, where the SD was higher, this indicated that the data is more spread out, hence the "mode" was chosen as the most representative value, i.e. External Air Temperature (C) and External Relative Humidity (%). For the Internal Relative Humidity (%), both values: "mode" and "mean" were the same, so this was the chosen value. See Table 13 for the summary of all these representative figures.

Thereafter, based on these descriptive statistics, all the daily averages were scrutinised across the full table for both winter and summer. The values that were same or similar to the chosen representative values were highlighted in green (see a sample of this on Table 12).

Table 12. Snapshot of a section of the winter season database created for the base-case study (This data can be investigated from various angles. Below is a brief sample of a section of the winter daily data. The full table hold data for the full year.



	A	B	C	D	E	F	G	
1	Date	Int Air Temp	Ext Air Temp	Air Humidity	Ext Rel Hum (%)			W
2	01 December 2016	22.456	7.671	81.078	83.375	Winter: Dec - Feb		
3	02 December 2016	22.24	6.167	82.365	84.625			
4	03 December 2016	21.823	3.738	85.515	95.042			
5	04 December 2016	21.666	3.479	86.08	93.958			
6	05 December 2016	22.269	6.333	85.287	92.25			
7	06 December 2016	21.56	3.208	85.341	90.958			
8	07 December 2016	21.205	2.508	88.083	92.667			
9	08 December 2016	22.517	10.042	86.773	93			
10	09 December 2016	22.36	7.671	82.792	84.5			
11	10 December 2016	21.392	3.417	82.724	68.708			
12	11 December 2016	20.685	1.9	88.27	86.5			
13	12 December 2016	21.456	3.163	85.336	88.75			
14	13 December 2016	22.198	6.642	84.175	87.25			
15	14 December 2016	22.439	8.05	83.679	90.208			
16	15 December 2016	22.079	5.421	83.777	91.833			
17	16 December 2016	22.254	6.483	84.649	93.208			
18	17 December 2016	22.322	6.779	82.951	90.625			
19	18 December 2016	22.259	5.925	84.953	90.833			
20	19 December 2016	22.441	8.208	84.481	93.417			
21	20 December 2016	22.441	7.925	82.825	88.625			
22	21 December 2016	22.394	7.487	82.817	88.25			
23	22 December 2016	22.488	9.021	83.319	88.042			
24	23 December 2016	22.582	9.712	85.712	92.625			
25	24 December 2016	22.638	11.025	83.492	92.5			
26	25 December 2016	22.631	10.242	85.327	92.25			
27	26 December 2016	22.438	7.937	82.001	83.083			
28	27 December 2016	22.576	9.971	87.063	97.208			
29	28 December 2016	22.559	9.433	85.238	96.292			
30	29 December 2016	22.36	7.292	85.221	96.833			
31	30 December 2016	22.037	5.171	82.631	88.542			
32	31 December 2016	22.339	7.158	82.687	84.458			
33	02 January 2017	22.328	9.29	83.312	88.434	Monday	Chosen typical we	
34	03 January 2017	22.393	7.775	81.817	81.208	Tuesday		
35	04 January 2017	22.425	7.846	80.642	80.083	Wednesday		
36	05 January 2017	22.204	6.454	85.551	92.333	Thursday		
37	06 January 2017	22.026	5.992	85.31	85.583	Friday		
38	07 January 2017	21.566	3.55	83.527	78.833	Saturday		
39	08 January 2017	22.3	7.479	87.344	93.958	Sunday		
40	09 January 2017	22.619	10.404	84.602	91.833			
41	10 January 2017	22.327	6.571	83.617	88.25			
42	11 January 2017	22.224	5.521	82.987	83.958			
43	12 January 2017	22.354	7.217	81.489	80.75			
44	13 January 2017	22.344	7.096	82.035	85.292			
45	14 January 2017	22.256	6.283	82.875	86.792			
46	15 January 2017	22.161	5.454	85.438	97.417			
47	16 January 2017	20.641	2.154	90.231	99.833			
48	17 January 2017	21.618	4.408	87.562	95.708			
49	18 January 2017	22.33	6.988	84.648	90.292			
50	19 January 2017	22.452	7.696	82.65	87			
51	20 January 2017	22.129	5.167	83.279	85			

Following this exercise, the week of the season that had the larger number of green cells was therefore chosen as the most representative week. Table 14 shows the chosen week in winter, based on the most representative parameters.

Table 13. Statistical values to select the most representative week of the winter season. Numbers in red have been selected after analsysis.

	Int Air Temp (C)	Ext Air Temp (C)	Int Humidity (%)	Ext Rel Hum (%)
MODE	22.456	7.671	84.136	93.958
MEDIAN	22.254	6.454	83.842	88.542
AVERAGE (MEAN)	22.029	5.952	84.136	87.617
STANDARD DEVIATION (SD*)	0.56	2.51	2.10	6.72

*use SD to select either mode or average

	Int Air Temp (C)	Ext Air Temp (C)	Air Humidity (%)	Ext Rel Hum (%)
TYPICAL WINTER WEEK:	22.0	7.7	84	94

Table 14. Based on the statistical values identified above, the most representative typical winter week was chosen.

Date	Int Air Temp (C)	Ext Air Temp (C)	Int Humidity (%)	Ext Rel Hum (%)		
02 January 2017	22.328	9.29	83.312	88.434	Monday	**Chosen typical week**
03 January 2017	22.393	7.775	81.817	81.208	Tuesday	
04 January 2017	22.425	7.846	80.642	80.083	Wednesday	
05 January 2017	22.204	6.454	85.551	92.333	Thursday	
06 January 2017	22.026	5.992	85.31	85.583	Friday	
07 January 2017	21.566	3.55	83.527	78.833	Saturday	
08 January 2017	22.3	7.479	87.344	93.958	Sunday	

<u>Trial 4:</u> Water content analysis.

Humidity is one of the various challenges faced by vertical farms, since its significantly affected by the capacity of achieving the right balance between ventilation rate and the internal temperature (Graamans et al. 2017; Jans-Singh et al. 2019). If the humidity is not suitable for the crops to thrive, this will affect their photosynthesis and therefore productivity (Davis and Hirmer 2015; Graamans et al. 2020). One of the methods of dehumidification is condensation (Kalantari et al. 2017a). The assisting software tool to this framework (HTB2) has a module that helps to calculate several parameters related to the behaviour of water content of the internal air (Figure 46). Therefore, this framework suggests to take advantage of this capabilities of the software to help the prediction of the water content and how this can be potentially coupled with water management strategies; potentially integrating this strategy with the recovery of the condensed water into the hydroponic systems, considering that hydroponic is the most popular method used to grow plants in vertical farms (Higgins 2016; Kozai et al. 2016b; Kalantari et al. 2017a).

This HTB2 module can be coupled in the future with models such as the mathematical model proposed by Davis and Hirmer (2015) which is based on the FAO-56 Penman Monteith Equation, aiming to quantify the effects of evaporative cooling on vertical systems.

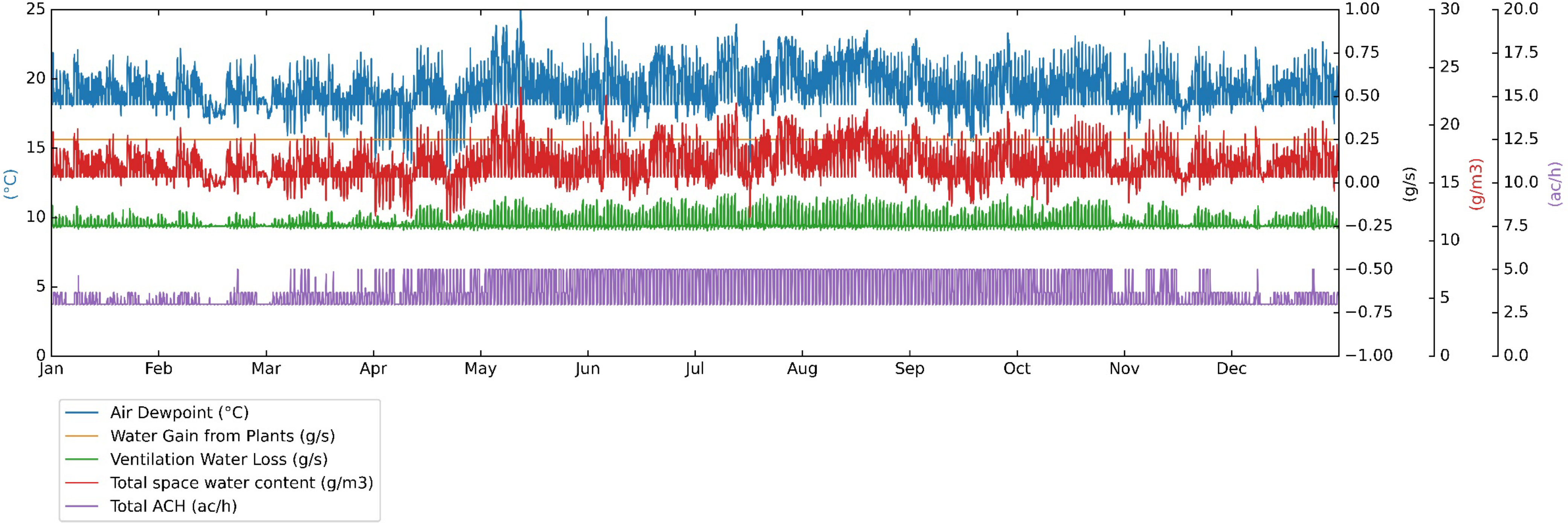


Figure 46. Parameters related to the behaviour of water.

<u>Trial 5:</u> Testing renewable energy potential.

HTB2 has the capability to calculate the potential of solar access falling on a building, to assess the suitability of renewable energy technology integration in/on buildings (i.e. simulate the amount of energy that can be harvested by having PV panels, for example). This is a valuable feature that can be exploited in a vertical farming simulation scenario. The potential to integrate renewable energy from sources such as solar photovoltaic can contribute to the sustainability of the system and the replicability of the business model. This is however a preliminary consideration for further research projects to build on, as it exceeds the ambition of this PhD research. Figure 47 below is a trial sample of this, using the data gathered from the base-case study.

Published literature states that the use of renewables would significantly help to advance the development of vertical farming (Al-Kodmany 2018; Avgoustaki and Xydis 2020; Graamans et al. 2020; Tablada et al. 2020), but there is not robust published evidence of any data and/or analysis on actual real cases, where the use of renewable energy has been used to supply the needs of a vertical farm (at the time that this research work).

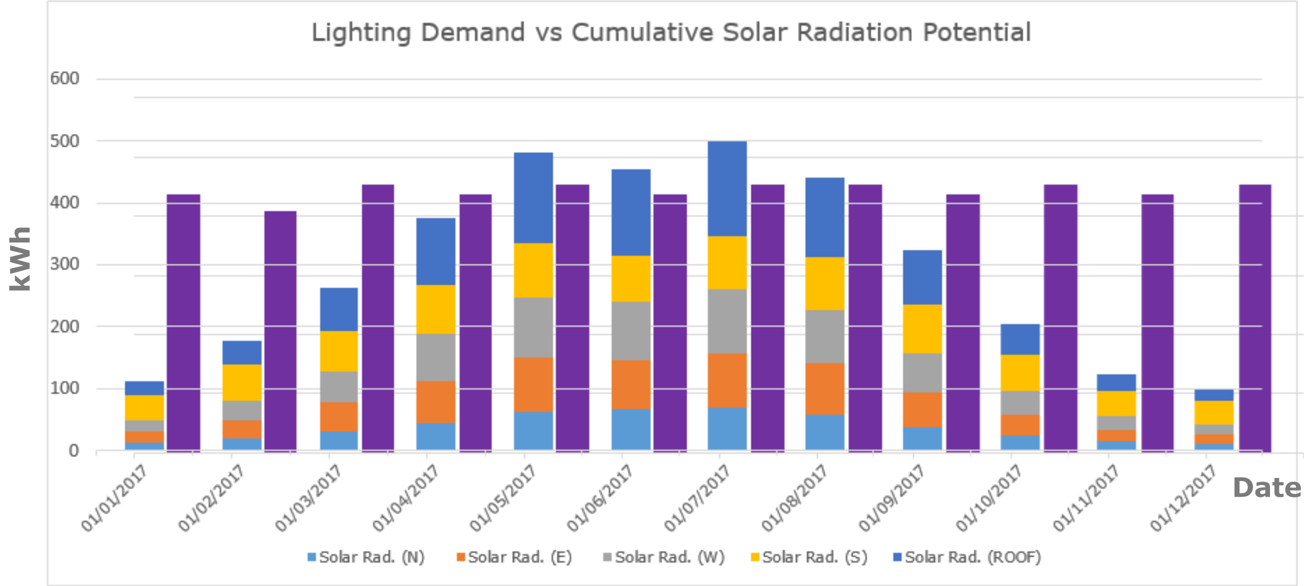


Figure 47. Sample study for renewable potential investigation: Lighting demand vs Solar radiation. The multi-colour bars represent the cumulative solar potential of all the facades+roof of the host building in kWh (solar radiation falling on all surfaces of this building) vs the purple bars represent the energy consumption of lighting, also in kWh. Monthly data for one full year (2016-2017).

During the simulation of the base case-study of this vertical farms analysis, the monthly energy consumption of the lighting required for the vertical farm was calculated with this framework method, for one full year. This lighting consumption (in energy terms) of the simulation has been included in the graph shown in Figure 47, represented by the purple bars. Each purple bar represents the monthly energy consumption of the lights of the vertical farm (in kWh). This data has been positioned next to the cumulative potential of harvesting energy from the sun, to potentially power these lights (also in kWh). This is what the multi-colour bars next to the purple bars represent, in the graph (Figure 47), i.e. the multi-colour bars show the total solar radiation falling on the various surfaces of the building, of this base-case study (in kWh). The host building of this case study is in the simple shape of a cube. The solar analysis was calculated considering the total solar radiation falling on each of the facades of this building (or cube), as well as the roof. The light blue shown in the multi-colour bars is the total solar radiation falling on the North Façade, the orange is the East Façade, the grey is the West Façade, the yellow is the South Façade and the darker blue is the whole roof of the building. The geolocation of the base-case study is Cardiff, Wales. Further characteristics of this base-case study can be found on section 5.5.1.1.

This exercise aims to show that if the host building of this simulated vertical farm could be covered perhaps with Building Integrated Photovoltaics (BIPV), a significant amount of energy could be generated to cover a large portion of the energy demand incurred by the lights. However, it must be noted that the amount of solar energy that can be harvested would be highly dependent on the efficiency of the installed technology (i.e. if the BIPV panels are only 20% efficient, then only 20% of the energy shown in the graph would be harvested). Hence, high efficiency of the technology is significant at the time of making significant investment decision of investing. This simulation framework could potentially be further developed to support this decision-making process for vertical farms.

5.6 Chapter Summary

This chapter provided a brief recount of the current level of knowledge found in the published literature. It discussed the shortcomings of existing research methods attempting to simulate vertical farms. Thereafter, detailed recount of the explored tools that had the potential to be use for the advancement of vertical farms and various arguments have been provided to indicate that HTB2 was the most suitable candidate to undertake the tasks at hand. The main characteristics in favour of selecting HTB2 are: flexibility, validated software, open-access, free of charge. This was followed by the development of a base-case study which assisted the process of the development of the simulation-based framework.

Chapter 6
Framework Implementation: GrowUp Urban Vertical Farm Case Study

"Humanity is now standing at a crossroads. We must now decide which path we want to take. How do we want the future living conditions for all living species to be like?"

(Greta Thunberg 2019)

6.1 Chapter Overview

This chapter presents the outcomes of testing the simulation framework developed in Chapter 5, using a comparison between a monitored case study and its simulation. The monitored case study was selected, the data was analysed to determine its suitability according to the aims of this thesis. This study provided evidence of how the monitored data could be directly compared to the simulated data. These key outcomes are important in the field of development of vertical farms because they provided evidence of potential uses of the simulation framework to assess the suitability and performance of vertical farms, as early as the design stage (before vertical farms are even built).

6.2 Introduction

The examples of vertical farms around the world illustrate the significant variations of existing vertical farms types, materials, and methods (or similar practices, such as plant factories, building integrated agriculture, etc) (Garg and Balodi 2014; Hughes 2018), as well as the many difficulties that different contexts pose to this practice (Khan and Ahmed 2017). Vertical farming is a viable agricultural practice (Gupta and Ganapuram 2019), but it has several challenges to overcome before it can become a widely used activity, since it needs significant optimisation (Hughes 2018; Kosorić et al. 2019; Butturini and Marcelis 2020).

There is a significant lack of cohesiveness and standardisation in this sector (Almeer et al. 2016; Shamshiri et al. 2018; Avgoustaki and Xydis 2020), not just in terms of the language used (or etymology) as highlighted and explored in the literature review chapter, but also in the relationship across all the relevant disciplines. The fact that vertical farming is a sector that requires interdisciplinary collaboration, progress in this sector tends to occur in silos instead of open-sourced research linking experts in the several areas that are essential for the optimum development of vertical farms (Storey et al. 2020). One thing seems to be clear across the literature in this sector: There is not one solution that fits all. All vertical farming systems have their own challenges, depending on their context, types of production, etc. There is a significant number of parameters that need to be considered to run a successful vertical farm (Benis et al. 2017a; Avgoustaki and Xydis 2020).

As previously mentioned, the current status of vertical farms around the world are commonly described as a sector still in its infancy (Al-Chalabi 2015; Higgins 2016; Jans-Singh et al. 2019; Farquhar 2020; Zimmerman-Loessl et al. 2020). As such, it is unsurprising that there are several knowledge-gaps (Higgins 2016; Khan and Ahmed 2017; Avgoustaki and Xydis 2020) and there is a significant amount of research required in order to help the vertical farming sector reach a higher level of maturity (Hughes 2018). Additionally, the outcomes of chapter 3 and 4 indicated that many vertical farming stakeholders (along with other relevant parties in the supply chain) are concerned about the limitations and challenges of the current status of vertical farms (Benis et al. 2018; Graamans et al. 2018). It is a well-known fact that, although viable, this is an expensive agricultural practice (Hughes 2018; Avgoustaki and Xydis 2020). Therefore, there are still contradicting arguments in the matter of the profitability potential of vertical farms and whether there is a financially enticing case for this practice. For instance, Hughes (2018) argues that the financial viability or a successful "business model" depends on many aspects, such as the types of crops, scale, level of automation, or others. Al-Kodmany (2018) explains that the economic feasibility of vertical farms is highly dependent on their design/size. He argues that multi-story vertical farms are not yet financially realistic. In his publication he outlines that despite the financial challenges, there are pioneering companies attempting to achieve high multi-story farms, highlighting Plantagon as one of these enterprises. Plantagon had the target to build a 17-storey vertical farm in Sweden (Kalantari et al. 2017b). This ambitious enterprise did not come to fruition, conversely, in 2019 an announcement was made with regards to the bankruptcy of the company Plantagon (Marston 2019). Nevertheless, in a parallel context, Al-Kodmany (2018) states that despite the financial difficulty attached to high-rise vertical farms, there has been a rapid growth of modest-scale vertical farms (approximately 3 to 5 storey-buildings, or smaller). In his publication he also questions the validity of the argument of the financial difficulties attached to vertical farms, comparing it to regular agriculture. Al-Kodmany (2018) elaborates on this topic explaining that current practices of food production and supply are increasingly suffering from not only economic problems, but also environmental endangerment and scarcity and these issues should be factored in.

Kalantari et al (2017b) describes a number of the economic benefits that vertical farming can offer, among these are the financial benefit of maximising land use, reducing food transport distances, the significant potential to use unused areas of the cities or repurposing abandoned buildings, opportunities for local economies to grow, amongst other benefits. These benefits are also echoed by other authors (Despommier 2010; Samangooei et al. 2016; Ward R et al. 2018).

The simulation framework developed in Chapter 5 and the trials conducted are a first step on establishing a viable tool with the corresponding simulation framework to assess the performance of vertical farms by recreating the behaviour in indoor environments. However, the complexities of the field and the difficulties of balancing the parameters, taking into account a holistic approach, makes it necessary to conduct a test of simulated vertical farms. This aligns with objective 3 of this thesis:

> **Objective 3: To test the simulation framework developed in order to assess an active vertical farm (case study). Including the assessment of the framework to allows the prediction of important parameters relevant to establishing an optimum environment required for the building to host a vertical farm indoors.**

6.3 Selection of the case study

In order to test the framework proposed and developed in Chapter 5, a site has been chosen to test the simulation framework on a real commercial vertical farm, as an active case study.

Details of the site were gathered via a collection of methods:

- Scoping study: to select case study (active and real, not virtual).
- Once the potential case study has been identified: Liaising with owner of the commercial vertical farms to establish the amount of data that can be gathered.
- Site visit: The author of this PhD visited the selected case study.
- Data gathering: The data shared by the owner of the vertical farm was analysed generating descriptive statistics and correlations and compared with simulated data of this research.
- Framework analysis: Based on the above study, the framework proposed and developed in chapter 5 has been used to recreate the conditions of the real case study in a simulation using the selected tool (HTB2).

6.3.1 Scoping study

The study started investigating the existing vertical farms in the market, based on the initial and extended literature review and state of the art study.

The aim of the Scoping study was to research and filter suitable candidates for conducting a field study and gathering of available data regarding vertical farms currently used methods and parameters. This methodology was selected as it allowed conducting a search of suitable vertical farms from different backgrounds and industries, while posing a broad quest for parameters and methods used within them (Daudt et al. 2013).

During the scoping study, a number of vertical farms stakeholders in the commercial and research fields were contacted. This led to a number of site visits to appraise viability to find a case study to use as part of this investigation (Table 15).

Table 15. Most relevant engagement during the scoping study

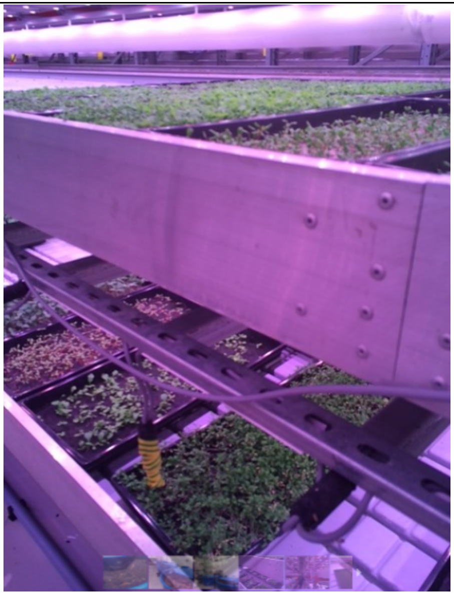
2017- Shanghai.

The author of this investigation contacted a research group at East China Normal University to undertake research collaboration in this area. The university agreed to provide access to their university facilities at the School of Ecology and Environmental Sciences to allow this research to assess opportunities to find a suitable case study (or case studies) in China, following a successful student mobility grant application with the Newton Fund. This visit was part of the scoping study to find active vertical farms willing to collaborate and share knowledge in this practice. No suitable candidates were found on this occasion (the trip was also interrupted due to unforeseen circumstances).

There were no tangible outcomes of this particular field trip, but the most significant learning from this visit was the first-hand experience and knowledge gained related to the high levels of confidentiality and privacy that is embedded within this industry in China. This seems to be similar in various other countries around the world, where very limited amount of data is published on vertical farms and active vertical farms are very private.

2018- London.

Site visit to an aquaponic vertical farm in London: GrowUp Urban Farm. The co-founder of the farm granted access to the site and agreed to share their monitoring data. This became the active vertical farm case study, used to test the simulation framework under development during this investigation.



2018- Bristol

Site visit to Grow Bristol, a vertical farm start-up conceived and developed in Bristol. This is a hydroponics farm, supplying leafy greens to local restaurants. This farm is at an early stage of development, no data was available for sharing at this stage, but Grow Bristol is eager to collaborate in R&D.

2018- Bristol

Another organisation based in Bristol is Lett Us Grow. This is a research and development organisation, mainly focused on the investigation of aeroponics systems for vertical farming. Including research on the impact of lighting, nutrients and other parameters that affect aeroponics plant growing. Their data has commercial sensitivity, hence not available for sharing in this occasion.

2018- Coventry

Site visit to Coventry to investigate the potential of research collaboration with the sisters organisations: Hydrogarden and V-Farm. Photographs were not allowed; therefore, images below are sourced from the public domain, available in their websites. Their data is also commercially sensitive, hence no possibility for data sharing.

The above were the most relevant events of the scoping study, nevertheless there were several other stakeholders in academia and industry that have been contacted as part of this study, for more details see Appendix 1. Based on above, the most suitable case study to be included in this analysis was chosen:

GrowUp Urban Vertical Farm (London).

6.3.2 Case study data analysis

GrowUp Urban Farm was the first commercial aquaponics vertical farm in the UK. It operated commercially in London from 2014 until 2017. Figure 48 shows the site location of the farm, which was based inside an industrial warehouse in Beckton.

Figure 48. Site location. London, UK

The farm used aquaponics and hydroponics to grow plants, as well as fish farming. Both systems are linked: the plant growing system and the fish tanks. The fish faeces produced the majority of the nutrients required in the soil-less system, where the plants are produced. The data used for the comparative analysis undertaken as part of this PhD project has been based on this farm in London. During the development of this study and following the various interaction with co-founder of GrowUp Farm, Tom Webster, it was revealed that there were plans to open a larger vertical farm. This is how the GrowUp Farm in London closed, to make all the necessary arrangements for this expansion. This is how GrowUp Development Lab opened in 2020, at the Agri-Epi Centre, at Harper Adams University, with the aim to build and develop a large scale state-of-the-art controlled environment vertical farm premises (GrowUp Farm Website).

Returning to the characteristics of the case study in question, besides sharing a full year monitored data from the vertical farm, the collaborator and co-founder of the farm, also provided detailed drawings of the premises. Figure 49, Figure 50 and Figure 52 provide details of the layout and vertical arrangements of the farming systems.

Figure 51 includes the photos taken by the author of this thesis during one of the site visits. These images focus on the two main chambers of this urban farm: the aquaculture chamber (where the fish farming takes place) and the plant growth chamber. The detailed drawings were used to calculated distances, areas and any other necessary data relevant for the construction and development of the virtual model of the simulation of this case study (using HTB2, as part of the framework development).

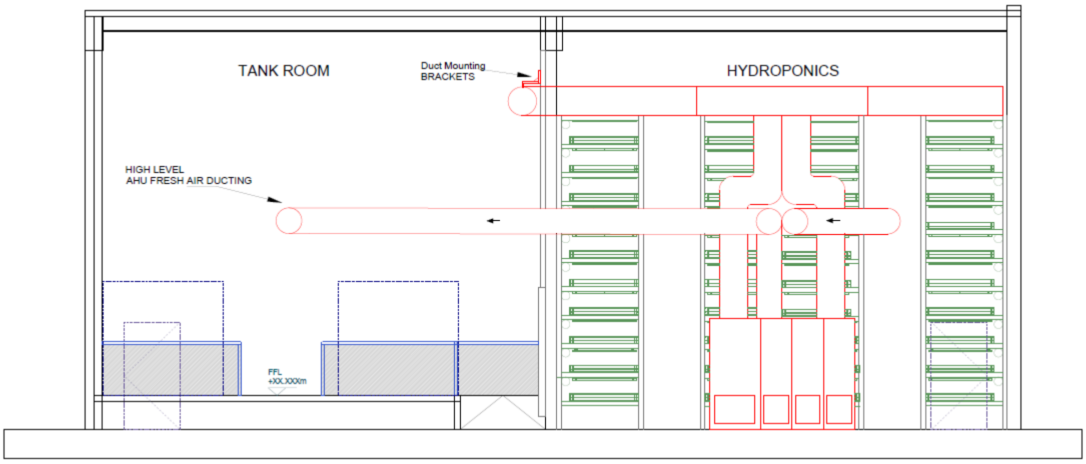


Figure 49. Section View (Front) of GrowUp Urban Farms- Case Study (Image courtesy of: Tom Webster, Co-Founder GrowUP)

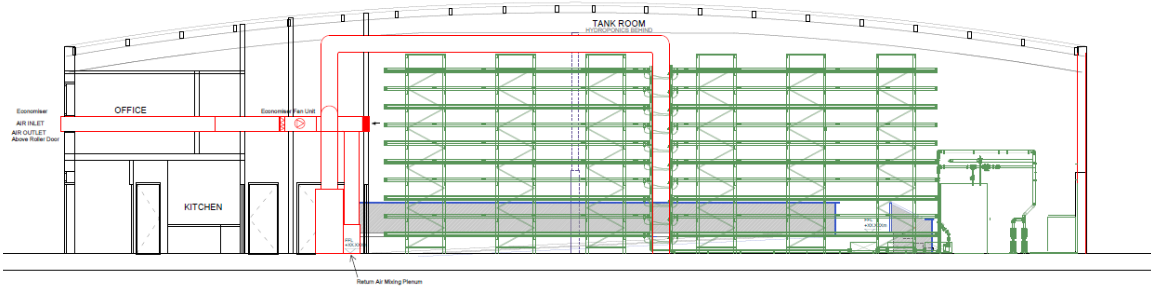


Figure 50. Section View (Side) of GrowUp Urban Farms- Case Study (Image courtesy of: Tom Webster, Co-Founder GrowUP)

Figure 51. Inside GrowUp vertical farm
(a) Aquaculture chamber (fish) (b) Plant growth chamber (leafy greens)
(Images: Taken by author during site visit)

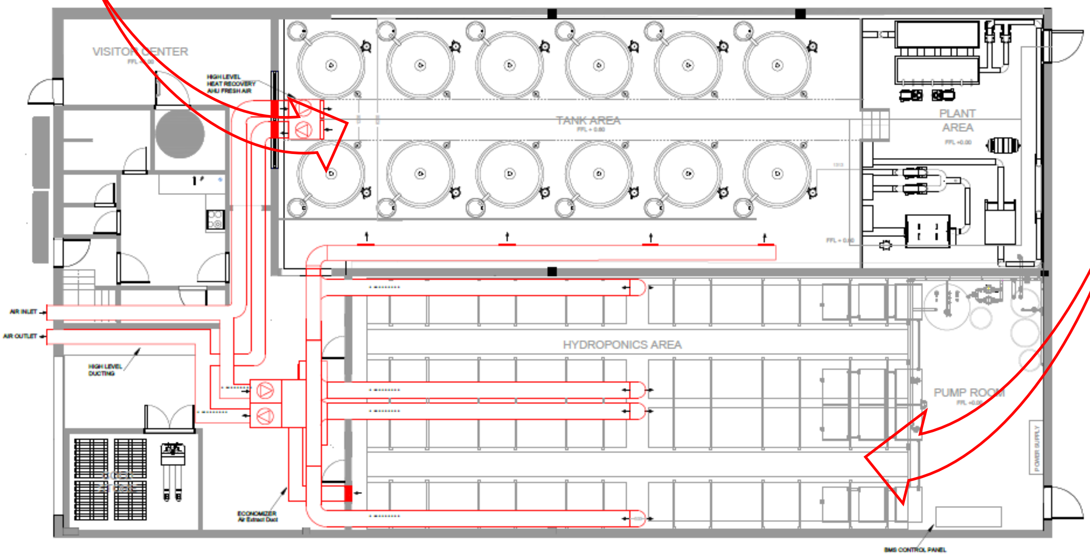


Figure 52. Plan view of GrowUp Urban Farms- Case Study
(Image courtesy of: Tom Webster, Co-Founder GrowUP)

Based on the information extracted from the drawings, the necessary characteristics to develop the simulation scenario were calculated. They are outlined in Table 16:

Table 16. Calculated values related to dimension and number of Plant growing trays/shelves

Trays/shelves length = 24 m
Trays/shelves width = 1.4 m
Trays/shelves Thickness = 0. 06 m
Trays/shelves Distance = 0.3 m
Total Planting tower height= 6 m
Total Planting trays/shelves= 40
Number of stacks/towers = 4
Area of towers' footprint = 134.4 m2
Total available grow area = 1,344 m2

The data shared by the owner of the farm is a detailed collection of hourly data of various parameters, which have been monitored for a period of a full year, from Nov 2016 until Nov 2017 (shared in Excel format). Some of the most relevant parameters included in this monitored data are specified in Table 17.

Table 17. Parameters of the monitored dataset

Monitored Parameter	**Unit**
Air Handling Energy Use (AHU)	kWh
Irrigation Energy Use	kWh
Lighting Energy Use	kWh
Lights ON (photoperiod)	Number of benches ON (grow trays)
Lights OFF (darkperiod)	Number of benches OFF (grow trays)
Indoor Temperature	Degrees Celsius (C^o)
Indoor Humidity (RH)	%
CO_2 Levels	Average PPm

The methodology for the input of data into the simulation tool has also been described in more detail in the previous chapter (Chapter 5, section 5.5.1.3)

6.4 Results and discussion

6.4.1 Testing the framework

Following the framework proposed in Chapter 5, this section will follow the steps and parameters outlined by the suggested framework in order to appraise its applicability on a real case study (i.e. a commercially active vertical farm). Thanks to the data shared by the owner of the vertical farm a direct comparative study can be made between the simulation developed as part of the proposed framework and the real vertical farm. Therefore, the data analysed here is: Monitored vs Simulated.

Framework in action

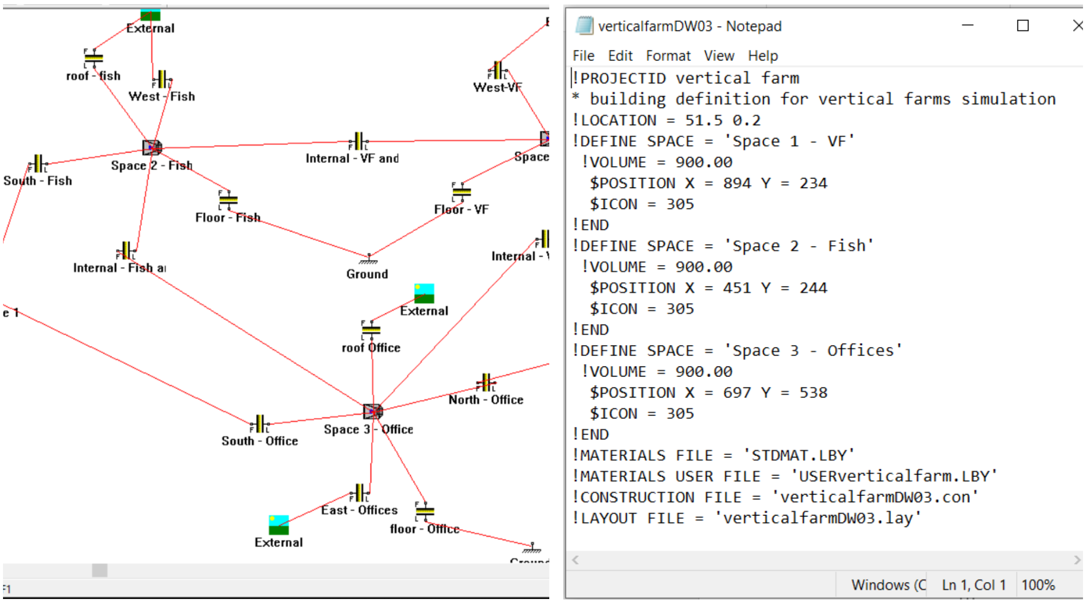
Stage 1: THE BUILDING

The characteristics of the host building of this vertical farm are outlined in Table 18. These details are the initial characteristics required to set up the simulation model, which are used to populate the HTB2 modules/files.

Table 18. Parameters and characteristics used for the simulation of the selected commercial Case Study: GrowUp Urban Farms

Parameters GrowUp Case Study		
Location	London	
Type of vertical farm	Aquaponics/Hydroponics	
Type of host building	Industrial Unit, no windows	
Size of building	30m x 15m x 6m(high)	
Building Volume	900 m^3	
Temperature	Photoperiod	21 – 25°C
	Darkperiod	18 – 22 °C
Lighting Hours	(i.e. Photoperiod)	16 hours (08:00 – 23:59)
Light Power	LED multi-chips	126,720 Watts (total)

Figure 53 provides snapshot of the view of the case study in HTB2. In the schematic view, Figure 53(a), the building has been designed with three separate spaces: one for the aquaculture chamber (fish), another for the plants' grow room (with all the vertical shelves/trays) and the third space is dedicated to offices and other uses within the farm. All of these details are input using the schematic tool of HTB2. Figure 53(b) shows that the geolocation has been recorded (coordinates) and that the volume of the various spaces of the building have been included. The information about the facades orientation and areas have also been included at this stage of the building characteristics.



```
!PROJECTID vertical farm
* building definition for vertical farms simulation
!LOCATION = 51.5 0.2
!DEFINE SPACE = 'Space 1 - VF'
 !VOLUME = 900.00
  $POSITION X = 894 Y = 234
  $ICON = 305
!END
!DEFINE SPACE = 'Space 2 - Fish'
 !VOLUME = 900.00
  $POSITION X = 451 Y = 244
  $ICON = 305
!END
!DEFINE SPACE = 'Space 3 - Offices'
 !VOLUME = 900.00
  $POSITION X = 697 Y = 538
  $ICON = 305
!END
!MATERIALS FILE = 'STDMAT.LBY'
!MATERIALS USER FILE = 'USERverticalfarm.LBY'
!CONSTRUCTION FILE = 'verticalfarmDW03.con'
!LAYOUT FILE = 'verticalfarmDW03.lay'
```

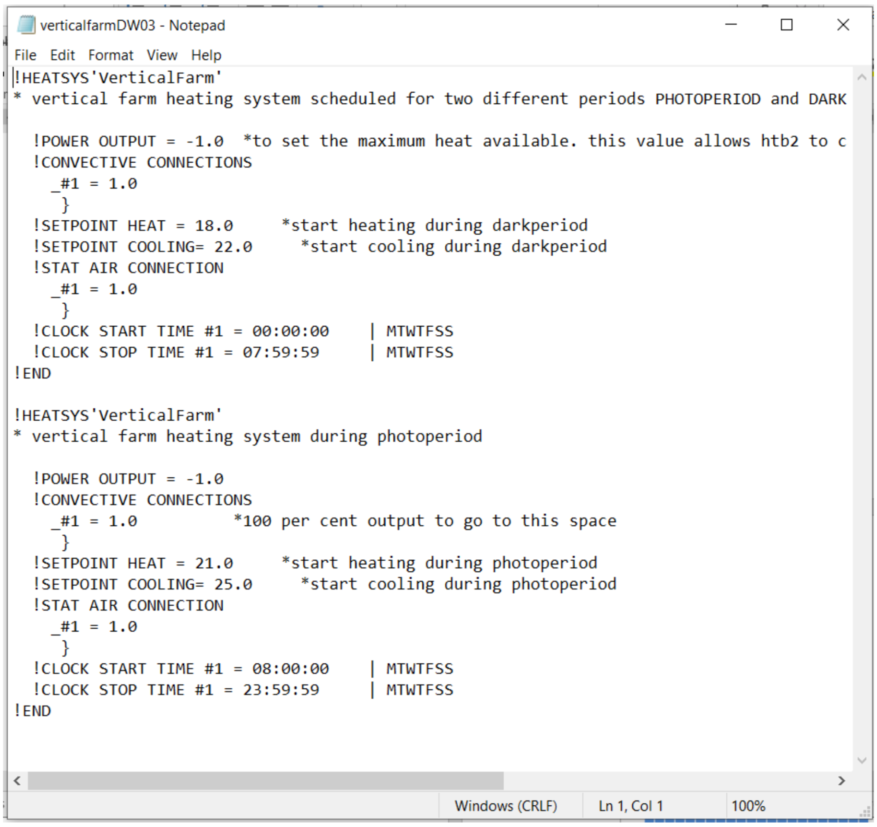
Figure 53. View of GrowUp urban farm in HTB2:
(a) Schematic view and (b)Configuration file

Stage 2: THE SIMULATION PAREMETERS

Services:

- Heating:

Two sets of requirements were also simulated for this case study: photoperiod and darkperiod. Figure 54 shows the heating file specifying the requirements for both different periods. The file shows that the ranges of optimum temperature specified here are: 18°C to 22°C for darkperiod and 21°C to 25°C for photoperiod. These values can vary according to desired specifications. This case study has an air handling unit to control the indoor environment.



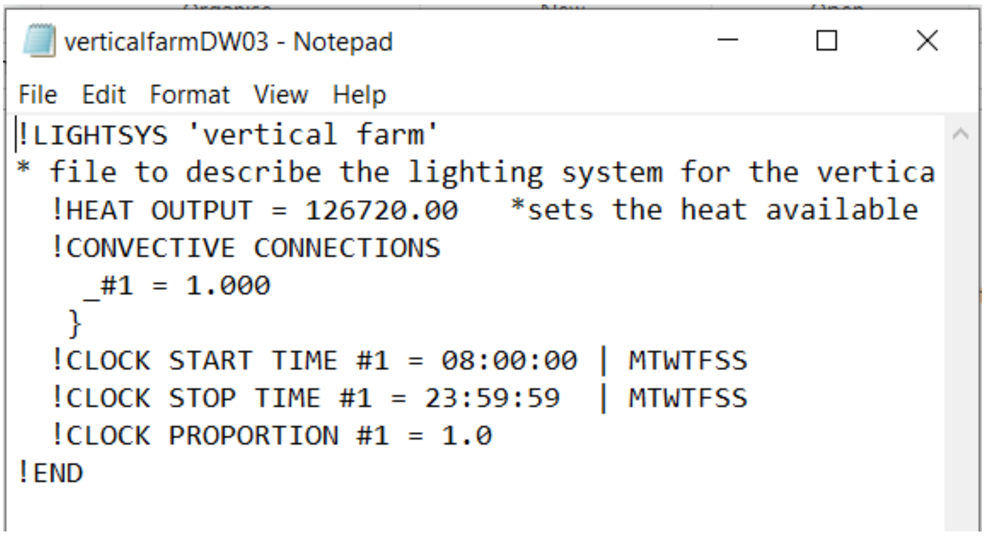
```
!HEATSYS'VerticalFarm'
* vertical farm heating system scheduled for two different periods PHOTOPERIOD and DARK

  !POWER OUTPUT = -1.0  *to set the maximum heat available. this value allows htb2 to c
  !CONVECTIVE CONNECTIONS
    _#1 = 1.0
     }
  !SETPOINT HEAT = 18.0     *start heating during darkperiod
  !SETPOINT COOLING= 22.0     *start cooling during darkperiod
  !STAT AIR CONNECTION
    _#1 = 1.0
     }
  !CLOCK START TIME #1 = 00:00:00    | MTWTFSS
  !CLOCK STOP TIME #1 = 07:59:59     | MTWTFSS
!END

!HEATSYS'VerticalFarm'
* vertical farm heating system during photoperiod

  !POWER OUTPUT = -1.0
  !CONVECTIVE CONNECTIONS
    _#1 = 1.0          *100 per cent output to go to this space
     }
  !SETPOINT HEAT = 21.0     *start heating during photoperiod
  !SETPOINT COOLING= 25.0     *start cooling during photoperiod
  !STAT AIR CONNECTION
    _#1 = 1.0
     }
  !CLOCK START TIME #1 = 08:00:00    | MTWTFSS
  !CLOCK STOP TIME #1 = 23:59:59     | MTWTFSS
!END
```

Figure 54. Snapshot of the heating file with details of expected optimum temperature and times/schedules for the different periods (photo and dark)

- Lighting power:

Figure 55. LED Lighting arrangement at GrowUp urban Farm
(Images: Taken by author during site visit)

The lighting system used in this case study is LED light (Figure 55); therefore, similar calculations are used to the ones described in the base-case study (Chapter 5, section 5.5.1.3, Lighting subsection). In this occasion each tray will require approximately 3,168 Watts, based on its grow area. This number was thereafter multiplied by 40 trays, the final figure being = 126,720 Watts. This value is therefore input in the lighting module of the support simulation tool (HTB2), see Figure 56.



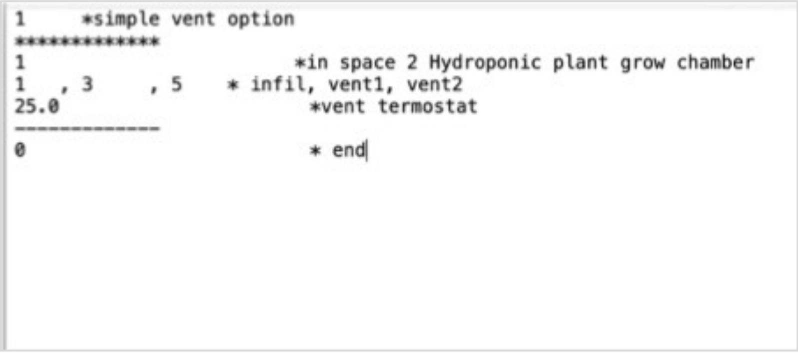
```
!LIGHTSYS 'vertical farm'
* file to describe the lighting system for the vertica
  !HEAT OUTPUT = 126720.00   *sets the heat available
  !CONVECTIVE CONNECTIONS
     _#1 = 1.000
    }
  !CLOCK START TIME #1 = 08:00:00 | MTWTFSS
  !CLOCK STOP TIME #1 = 23:59:59  | MTWTFSS
  !CLOCK PROPORTION #1 = 1.0
!END
```

Figure 56. Lighting File - GrowUp Urban Farm case study

- Ventilation file:

No specific data regarding air changes per hour (ACH) was provided from the monitored data. Therefore, to develop the simulation, some assumptions were considered. These assumptions were based on the learning from the research developed in the previous chapter, during the development of the base-case study. The outcomes of "Trial 1" of the simulation framework development chapter were consider for this case study (Chapter 5, section 5.5.2). In "Trial 1", it was outlined how there is not transparency or data sharing in terms of ventilation rates of vertical farms in the literature. Authors such as Jans-Singh et al (2019), Graamans et al (2018) and Benis et al (2017b) do make tentative suggestions about the ventilation rates used in their investigation, but these publications are also not clear on the accuracy and origin of these values and there is not consistency on this parameter across the literature. Due to the doubt regarding the parameters referenced in the literature, the author searched for further clarification on this topic, hence two of the main published authors on this topic where contacted and question about the parameters they have used in their work. These two authors were: Graamans and Benis. Both responded the queries in a similar fashion, explaining that they could not provide further clarification on the values used for ventilation, since they only undertake virtual scenarios, not real case studies and there were uncertainties on the accuracy of the ventilation rates they use.

In conclusion, based on the analysis undertaken during the "Trial 1" of the previous chapter, also making reference to the simulation results displayed in Figure 34 and 35 of the previous chapter, 5 air changes per hour (ACH) was used as a basic ventilation rate, as it was the most suitable from the findings during the base-case study (Figure 57).



```
1     *simple vent option
*************
1                        *in space 2 Hydroponic plant grow chamber
1   , 3     , 5    * infil, vent1, vent2
25.0                      *vent termostat
-------------
0                         * end
```

Figure 57. Ventilation file GrowUp-case study

- Occupancy file:

The occupancy module of HTB2 is normally HTB2 to account for the incidental heat and water vapour gains resulting from occupants. (Alexander 2008). These characteristics has been discussed in the previous chapter during the development of the base case study (Chapter 5, section 5.5.1.3), where it has been explained that for the purpose of the simulation of vertical farms the incidental heat gains have been disabled and only water vapour gains are being integrated in these simulations. Hence, this model aims to simulate the interaction of the water counterbalance and humidity of vertical farms in relation to the building materials, the characteristics of the indoor environment, as well as the influence of the outside weather. The possibility to calculate the behaviour of the water vapour in vertical farms is a valuable characteristic, since it can allow to calculate dew points and other relevant values, which are particularly relevant in this field. This characteristic has particular significance and it would be encouraged to be further explored in future research development projects, since the outcome of these calculations are relevant to create strategies to take advantage of the indoors condensed water, which can thereafter be used and “reintegrated” in the water system of a hydroponic farm.

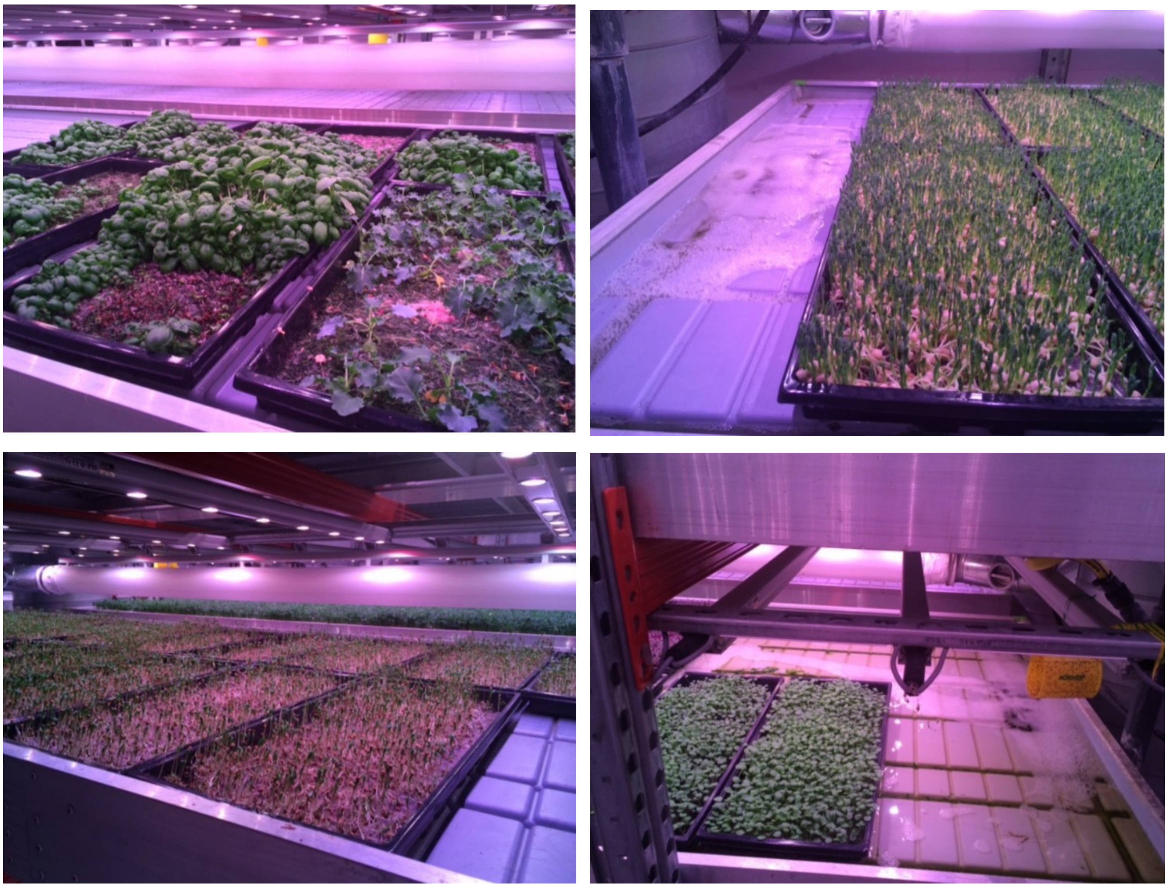


Figure 58. Images showing the grow trays (shelves) in GrowUp Urban Farm (Images: Taken by author during site visit)

As discussed in the previous chapter, HTB2 has not been designed to have “plants” as the occupants of a building. Therefore, to allow the software to account for the characteristics of the plants inside the farm, the occupancy file has been manipulated to include the water vapour characteristics, but not the incidental heat (see Chapter 5, section 5.5.1.3). Nevertheless, this manipulation is only a raw approximation to the reality. As it can be seen in Figure 58, a vertical farm will have different kinds of plants and the growing trays will not always be full to its maximum capacity, but developing software of this kind will bring the vertical farming world closer to find tools to assess, analyse and predict efficiency, in order to improve its productivity and better plan future projects. Nonetheless, the fact of software tools is that they can only “mimic” reality and all computer programs must have some level of estimation and approximation, this study is not different. HTB2 is a validated software tool that has been used for several years to develop reliable building physics simulations. It was designed to simulate humans as the main occupants of buildings, nevertheless, the way it calculates the incidental heat gains resulting from people is also averaged and estimated, this has been found during the scrutiny of the software by the author of this thesis. In a similar fashion, this study uses values found in literature to create an estimated water vapour gains from plants, to be included in the simulation. This estimation is by no means the case for all types of plants, but all this data is traceable and can be changed and tailored to different characteristics of other scenarios. By making assumptions, the accuracy of any simulation is reduced, but this investigation attempted to make assumptions only based on figures found on peer-reviewed journal papers and integrated in the simulation process following the rules established in the HTB2 simulation methodology. These considerations have been followed with the aim to achieve results of vertical farm simulations that can be as reliable as any other simulation undertaken with HTB2.

To bring this simulated scenario closer to the reality, it would require collaborative work from various experts, hence this is beyond the boundary of this PhD project. To overcome the limitations imposed by the software, this investigation made the necessary approximations to undertake the calculations. These are explained in the previous chapter, where the viability of the developed framework is demonstrated with the base-case scenario. The same process is now followed here to calculate the characteristics of this different case study, which is based on the parameters of a real vertical farm (GrowUp Urban Farm) and the values of this case study are compared between simulated data vs monitored data.

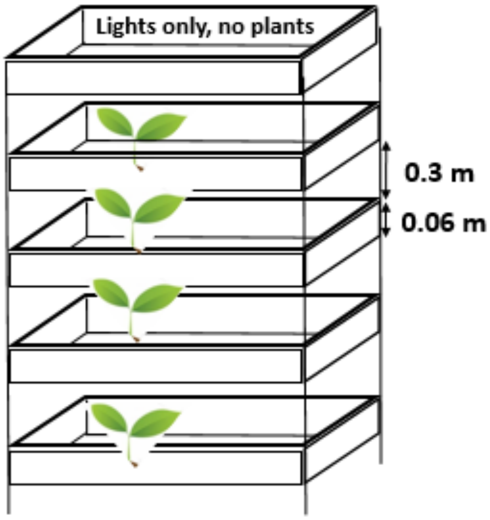


Figure 59. Growing trays

Based on total area of the growing trays, an approximate number of plants was calculated, using the drawings of the real vertical farm (GrowUp). Figure 59 is a representative schematic of the growing trays arrangement, but the total number of trays and growing area was calculated using the information provided by the owner of the real vertical. The drawings of the site provided clear accurate measurements for both: the building and the growing trays/towers. These drawing have been previously shown in Figures 49, 50 and 52. Based on the number of trays and growing area (total of 1,344m^2) of this vertical farm (summary of these figures have been previously shown in Table 16), it was calculated that, when full, GrowUp Urban farms has the capacity to cultivate 57,600 plants (note that the real vertical farm is significantly larger than the base-case study). Therefore, to develop the simulation scenario of the GrowUp farm, the number of "people" occupying the building has been proportionally increased also. The calculations have been extrapolated to reflect the larger grow area and the calculations are described below. Following the same process as the one established in the previous session (Chapter 5, section 5.5.1.3, "occupancy file") and based on the values found in the literature (Tenwolde and Pilon 2007), the water vapour released from plants and people could be compared using these numbers:

(1) One plant can release approximately 2.5 grams per hour (g/h) and

(2) One person can release approximately: 300 grams per hour (g/h)

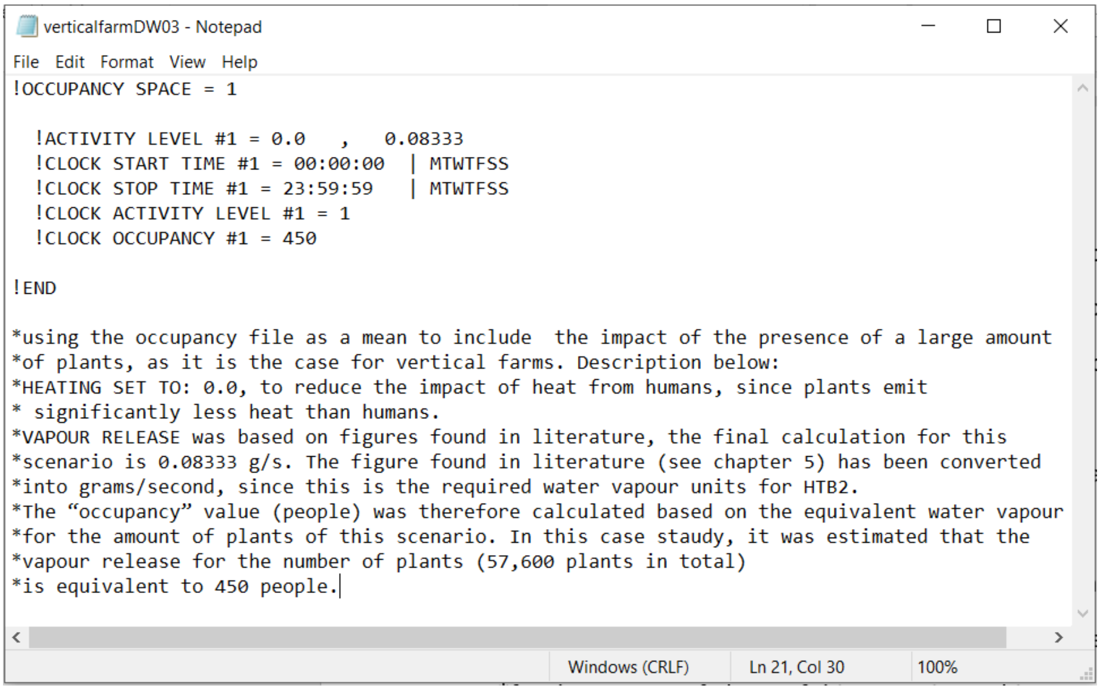
These values were compared to calculate equivalent figures and then converted to the units required by HTB2 (grams per second, g/s). Simple mathematical calculations were used to get the approximate values for the simulation:

- 300 / 2.5 = 120 i.e. 120 plants could produce an approximate amount of water vapour equivalent to 1 person.
- As mentioned above, GrowUp Vertical farm has been estimated to have the capacity to host/grow 57,600 plants (with the available growing areas)
- If 57,600 (plants) is divided by 120 plants (calculated in the first bullet point above), the resulting number will provide an estimated equivalent number of number of people required to produce similar amount of water.
  57,600 / 120 = 450 people.
- From the same reference, the water vapor produced by people is 300 g/h, but HTB2 uses the units g/s (grams per second), hence the conversion was calculated as:
  300 g/h / 3600second = 0.08333 g/s
  This is the water vapour figure also used for this simulation.

In summary, the calculations above resulted in the following values that would be used as the key inputs for the required by HTB2's occupancy file of this base-case study:

- Heat output (in Watts): **0 W**
- Water vapour (in grams per second): **0.08333 g/s**
- Number of occupants: **450 people** (which is the equivalent of the 57,600 plants that are estimated to occupy the GrowUp vertical farm)

These values can be seen in Figure 60.



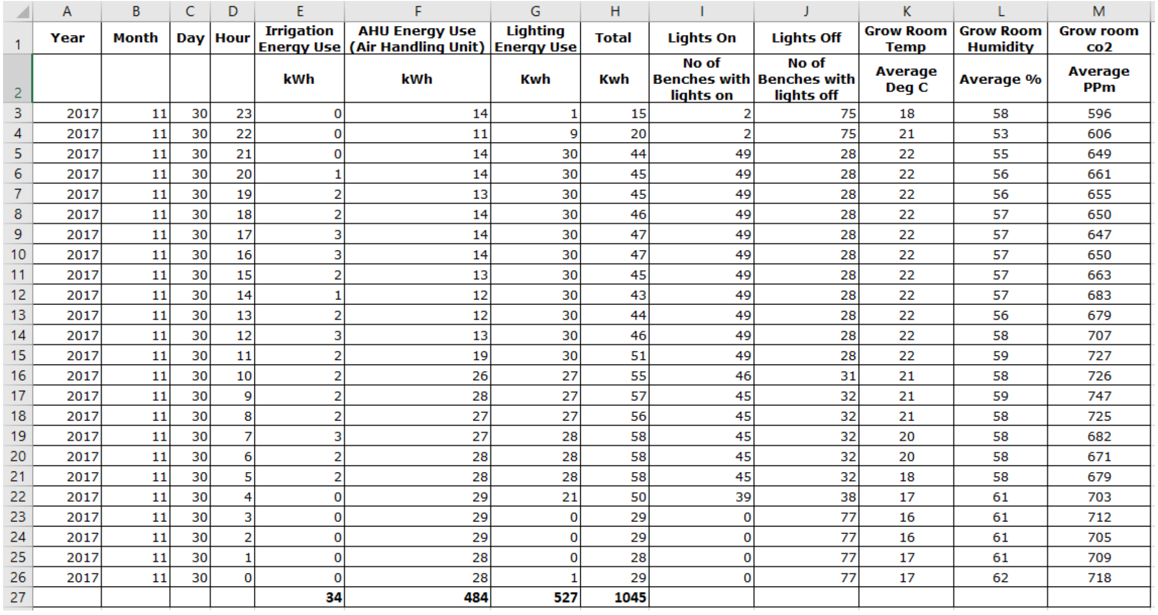
```
!OCCUPANCY SPACE = 1

  !ACTIVITY LEVEL #1 = 0.0    ,   0.08333
  !CLOCK START TIME #1 = 00:00:00   | MTWTFSS
  !CLOCK STOP TIME #1 = 23:59:59    | MTWTFSS
  !CLOCK ACTIVITY LEVEL #1 = 1
  !CLOCK OCCUPANCY #1 = 450

!END

*using the occupancy file as a mean to include  the impact of the presence of a large amount
*of plants, as it is the case for vertical farms. Description below:
*HEATING SET TO: 0.0, to reduce the impact of heat from humans, since plants emit
* significantly less heat than humans.
*VAPOUR RELEASE was based on figures found in literature, the final calculation for this
*scenario is 0.08333 g/s. The figure found in literature (see chapter 5) has been converted
*into grams/second, since this is the required water vapour units for HTB2.
*The “occupancy” value (people) was therefore calculated based on the equivalent water vapour
*for the amount of plants of this scenario. In this case staudy, it was estimated that the
*vapour release for the number of plants (57,600 plants in total)
*is equivalent to 450 people.
```

Figure 60. “Occupancy” File - GrowUp Urban Farm case study

6.4.2 Data analysis of Case Study

The owner of the vertical farm shared historical data from one year (from November 2016 until October 2017). In order to include this data for this analysis, further detailed investigation of the data took place as part of this research, as this was necessary to understand its value and suitability for the present study. Table 19 provides a snapshot of the type of data that have been provided, which included indoor environment parameters such as internal air temperature, relative humidity and CO_2 levels, as well as energy usage of lighting, irrigation and air handling unit. This data represents a good fit with the type of data analysis that has been undertaken as part of the framework (simulation-based) developed in this PhD research.

Table 19. Sample of the data provided by commercial research collaborator of the case study (GrowUp Urban Farm)



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	**Year**	**Month**	**Day**	**Hour**	**Irrigation Energy Use**	**AHU Energy Use (Air Handling Unit)**	**Lighting Energy Use**	**Total**	**Lights On**	**Lights Off**	**Grow Room Temp**	**Grow Room Humidity**	**Grow room co2**
2					**kWh**	**kWh**	**Kwh**	**Kwh**	**No of Benches with lights on**	**No of Benches with lights off**	**Average Deg C**	**Average %**	**Average PPm**
3	2017	11	30	23	0	14	1	15	2	75	18	58	596
4	2017	11	30	22	0	11	9	20	2	75	21	53	606
5	2017	11	30	21	0	14	30	44	49	28	22	55	649
6	2017	11	30	20	1	14	30	45	49	28	22	56	661
7	2017	11	30	19	2	13	30	45	49	28	22	56	655
8	2017	11	30	18	2	14	30	46	49	28	22	57	650
9	2017	11	30	17	3	14	30	47	49	28	22	57	647
10	2017	11	30	16	3	14	30	47	49	28	22	57	650
11	2017	11	30	15	2	13	30	45	49	28	22	57	663
12	2017	11	30	14	1	12	30	43	49	28	22	57	683
13	2017	11	30	13	2	12	30	44	49	28	22	56	679
14	2017	11	30	12	3	13	30	46	49	28	22	58	707
15	2017	11	30	11	2	19	30	51	49	28	22	59	727
16	2017	11	30	10	2	26	27	55	46	31	21	58	726
17	2017	11	30	9	2	28	27	57	45	32	21	59	747
18	2017	11	30	8	2	27	27	56	45	32	21	58	725
19	2017	11	30	7	3	27	28	58	45	32	20	58	682
20	2017	11	30	6	2	28	28	58	45	32	20	58	671
21	2017	11	30	5	2	28	28	58	45	32	18	58	679
22	2017	11	30	4	0	29	21	50	39	38	17	61	703
23	2017	11	30	3	0	29	0	29	0	77	16	61	712
24	2017	11	30	2	0	29	0	29	0	77	16	61	705
25	2017	11	30	1	0	28	0	28	0	77	17	61	709
26	2017	11	30	0	0	28	1	29	0	77	17	62	718
27					**34**	**484**	**527**	**1045**					

Different data queries were established, and thorough checks of the monitored data took place in the first instance, before attempting to compare this monitored data to the simulation data developed with this framework. Figure 61 is a sample of trials and investigation that took place to scrutinise the monitored data in the first instance.

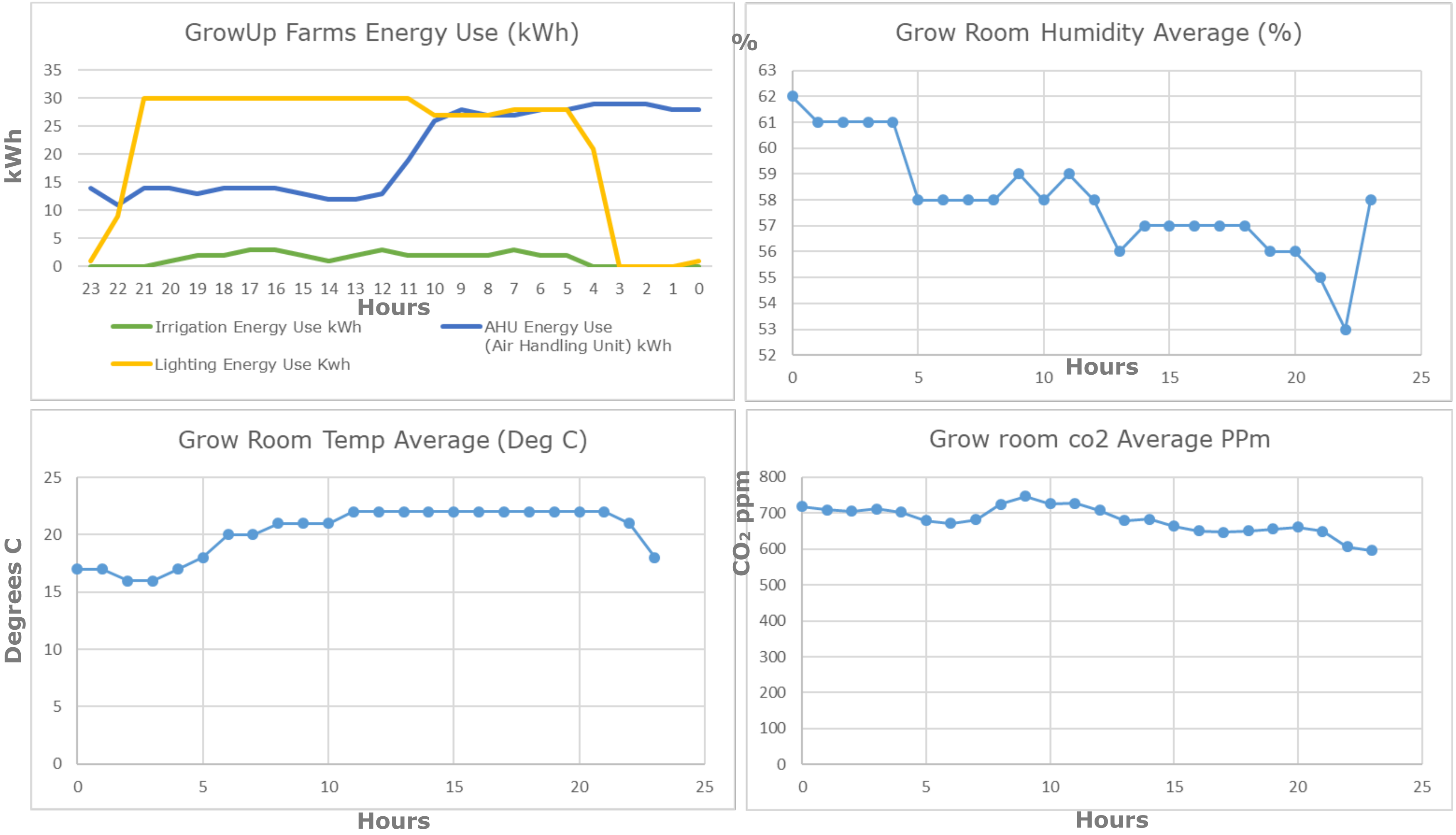


Figure 61. Graphs of sample data of different queries and scrutinising process of the monitored data to appraise suitability for the case study: 24 hours data (X-axis) in this example, (GrowUp Urban Farm).

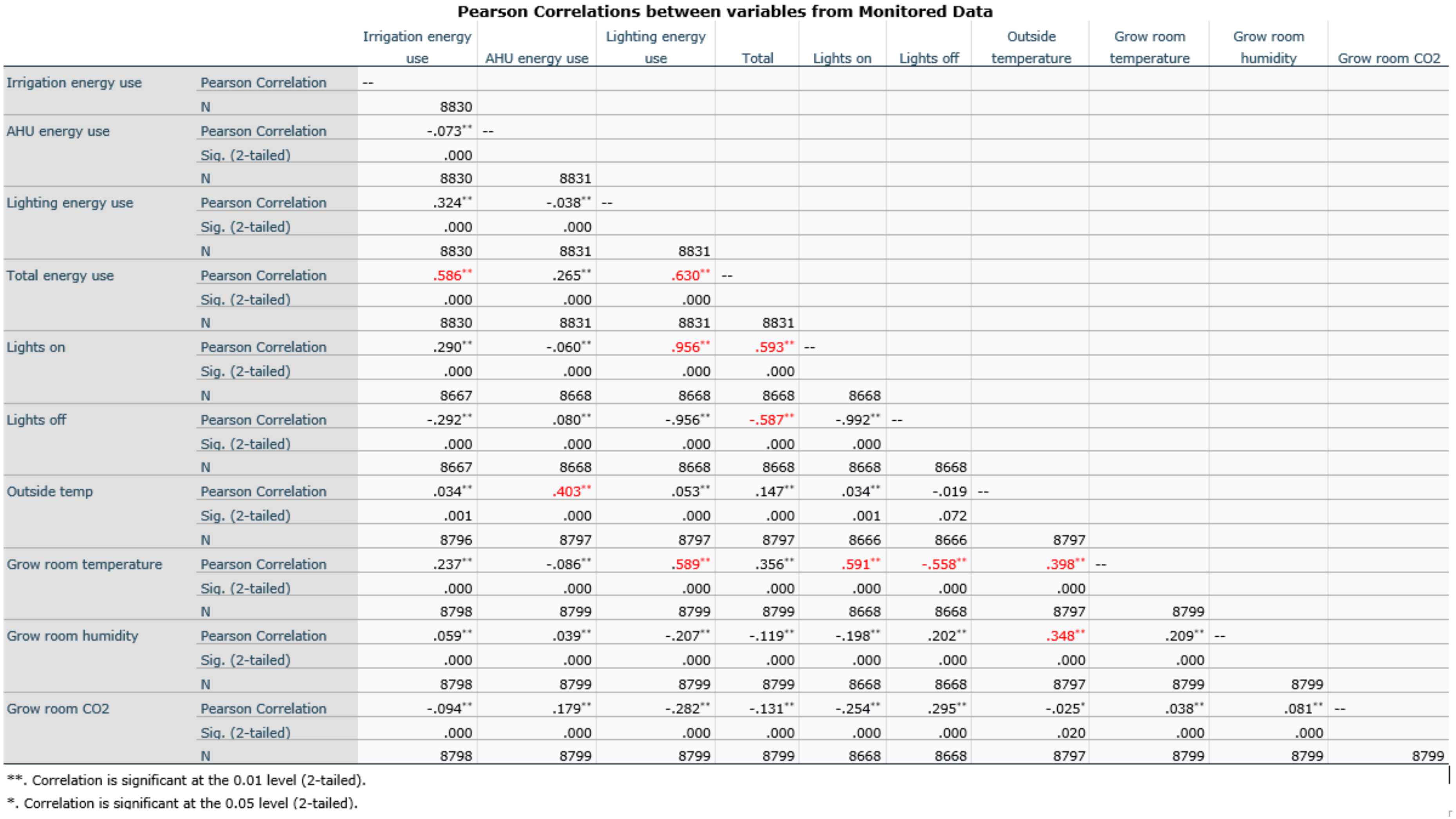
The next step was to identify if there is any correlation between the parameters provided and to identify which parameters could be compared to simulated data, using the framework proposed in Chapter 5.

Following the initial scrutiny of the data, statistical analysis was used to assess the correlation of the monitored data outlined above. Table 20 presents the Pearson correlation between the variables shared from GrowUp Urban Farm. The numbers in red represent the highest correlation and the most noticeable and interesting correlations found in this analysis are described below:

- The highest correlation for the total energy use was with the variables related to lighting: lighting energy use ($r = .63$, $p < .05$), lights on and lights off ($r = .593$, $r = -.587$, both $p < .05$). Followed by the irrigation energy use ($r = .586$, $p < .05$).
- The relationship between the outside and the grow rooms was evidenced with the correlations between the outside temperature and the energy used by the air handling unit (AHU) ($r = .403$, $p < .05$), grow room temperature ($r = .398$, $p < .05$) and grow room humidity ($r = .348$, $p < .05$).

This analysis allows to identify two key factors: the high influence of the lighting system on the total energy use, and the influence between the exterior of the building (outside temperature and humidity) and interior variables (air handling unit energy use, temperature, and humidity). These significant observations will be discussed in final section of this chapter.

Table 20. Statistical analysis of the monitored data. Numbers in red indicate high correlation.



Pearson Correlations between variables from Monitored Data

		Irrigation energy use	AHU energy use	Lighting energy use	Total	Lights on	Lights off	Outside temperature	Grow room temperature	Grow room humidity	Grow room CO2
Irrigation energy use	Pearson Correlation	--									
	N	8830									
AHU energy use	Pearson Correlation	-.073**	--								
	Sig. (2-tailed)	.000									
	N	8830	8831								
Lighting energy use	Pearson Correlation	.324**	-.038**	--							
	Sig. (2-tailed)	.000	.000								
	N	8830	8831	8831							
Total energy use	Pearson Correlation	.586**	.265**	.630**	--						
	Sig. (2-tailed)	.000	.000	.000							
	N	8830	8831	8831	8831						
Lights on	Pearson Correlation	.290**	-.060**	.956**	.593**	--					
	Sig. (2-tailed)	.000	.000	.000	.000						
	N	8667	8668	8668	8668	8668					
Lights off	Pearson Correlation	-.292**	.080**	-.956**	-.587**	-.992**	--				
	Sig. (2-tailed)	.000	.000	.000	.000	.000					
	N	8667	8668	8668	8668	8668	8668				
Outside temp	Pearson Correlation	.034**	.403**	.053**	.147**	.034**	-.019	--			
	Sig. (2-tailed)	.001	.000	.000	.000	.001	.072				
	N	8796	8797	8797	8797	8666	8666	8797			
Grow room temperature	Pearson Correlation	.237**	-.086**	.589**	.356**	.591**	-.558**	.398**	--		
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.000	.000			
	N	8798	8799	8799	8799	8668	8668	8797	8799		
Grow room humidity	Pearson Correlation	.059**	.039**	-.207**	-.119**	-.198**	.202**	.348**	.209**	--	
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.000	.000	.000		
	N	8798	8799	8799	8799	8668	8668	8797	8799	8799	
Grow room CO2	Pearson Correlation	-.094**	.179**	-.282**	-.131**	-.254**	.295**	-.025*	.038**	.081**	--
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.000	.020	.000	.000	
	N	8798	8799	8799	8799	8668	8668	8797	8799	8799	8799

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Following the above findings, the data was thereafter classified into the different parameters that could be compared to the results obtained from the simulation-based framework developed in Chapter 5. The most relevant comparative parameters identified are outlined in Table 21:

Table 21. Comparative parameters between monitored data and simulation.

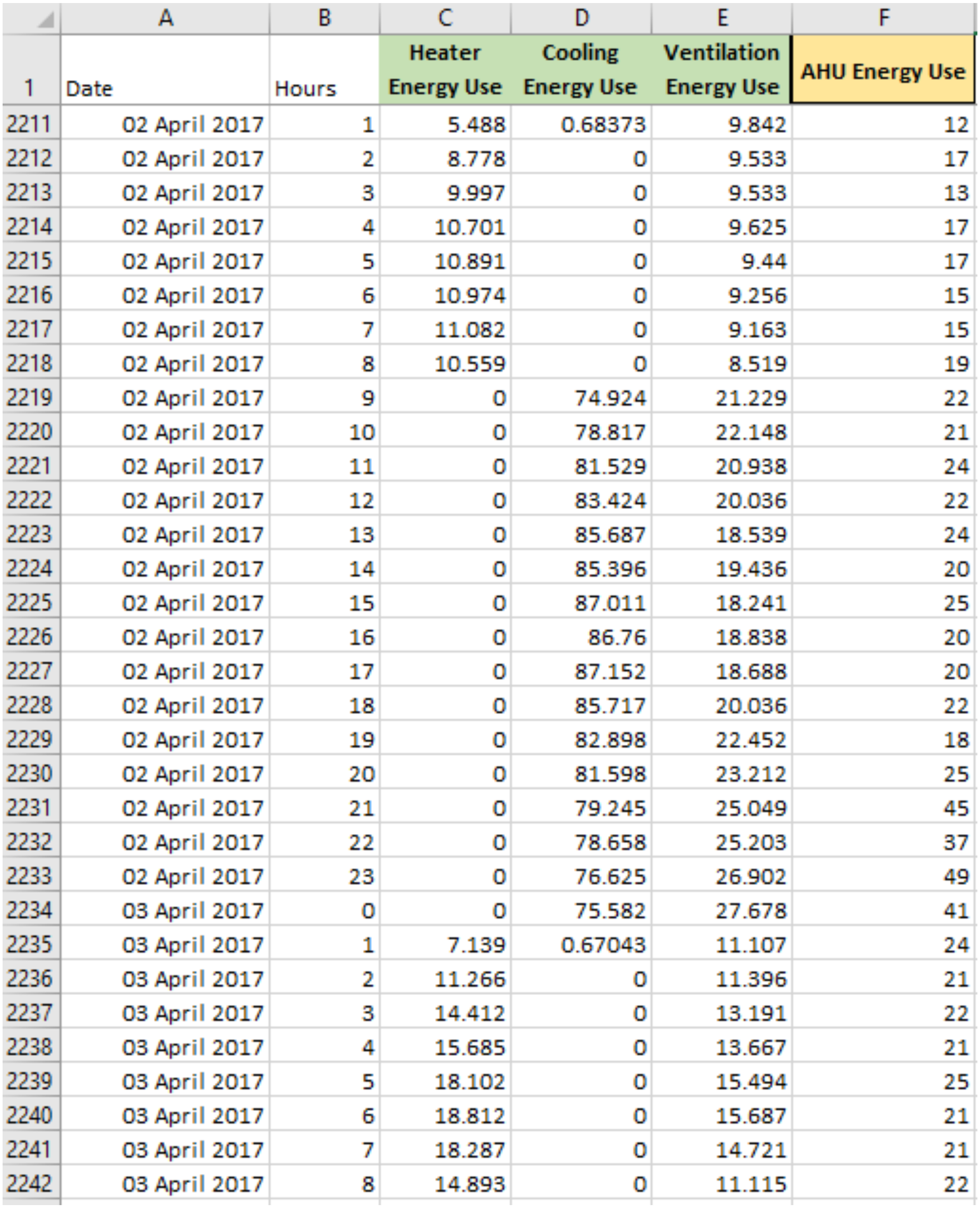
Monitored Data	**Simulated Data**
Lighting Energy Use (kWh)	Lighting Energy Use (kWh)
Lighting mode ON/OFF (i.e. Photoperiod/Darkperiod)	Lighting mode ON/OFF (i.e. Photoperiod/Darkperiod)
Air Handling Unit Energy Use (kWh)	Cooling, Heating and Ventilation Energy Use (kWh)
Inside Temperature (Degrees C)	Inside Temperature (Degrees C)
Relative Humidity (%)	Relative Humidity (%)

Table 22 is a snapshot of one of the databases created, assembling the results to compare Energy Use data (kWh) for the services of the vertical farm in this case (table 6). Other parameters are explored separately below.

- Services

An initial assumption aiming to establish comparisons between the simulated and the monitored data was that the air handling unit (AHU) figures were equivalent to the figures obtained for all the “services” included in the simulation, i.e., comparing the figures of monitored AHU vs the energy used by cooling, heating, and ventilating in the simulation. As a result, all the values were added, and the final consumption can be seen in Table 23. The final figures differed by a factor of 3.

Table 22. Snapshot of data comparing Energy Use (kWh) of the systems for both vertical farms: simulated (HTB2) vs monitored data (GrowUp Farm).The full table contains hourly data for the whole year.



	A	B	C	D	E	F
1	Date	Hours	Heater Energy Use	Cooling Energy Use	Ventilation Energy Use	AHU Energy Use
2211	02 April 2017	1	5.488	0.68373	9.842	12
2212	02 April 2017	2	8.778	0	9.533	17
2213	02 April 2017	3	9.997	0	9.533	13
2214	02 April 2017	4	10.701	0	9.625	17
2215	02 April 2017	5	10.891	0	9.44	17
2216	02 April 2017	6	10.974	0	9.256	15
2217	02 April 2017	7	11.082	0	9.163	15
2218	02 April 2017	8	10.559	0	8.519	19
2219	02 April 2017	9	0	74.924	21.229	22
2220	02 April 2017	10	0	78.817	22.148	21
2221	02 April 2017	11	0	81.529	20.938	24
2222	02 April 2017	12	0	83.424	20.036	22
2223	02 April 2017	13	0	85.687	18.539	24
2224	02 April 2017	14	0	85.396	19.436	20
2225	02 April 2017	15	0	87.011	18.241	25
2226	02 April 2017	16	0	86.76	18.838	20
2227	02 April 2017	17	0	87.152	18.688	20
2228	02 April 2017	18	0	85.717	20.036	22
2229	02 April 2017	19	0	82.898	22.452	18
2230	02 April 2017	20	0	81.598	23.212	25
2231	02 April 2017	21	0	79.245	25.049	45
2232	02 April 2017	22	0	78.658	25.203	37
2233	02 April 2017	23	0	76.625	26.902	49
2234	03 April 2017	0	0	75.582	27.678	41
2235	03 April 2017	1	7.139	0.67043	11.107	24
2236	03 April 2017	2	11.266	0	11.396	21
2237	03 April 2017	3	14.412	0	13.191	22
2238	03 April 2017	4	15.685	0	13.667	21
2239	03 April 2017	5	18.102	0	15.494	25
2240	03 April 2017	6	18.812	0	15.687	21
2241	03 April 2017	7	18.287	0	14.721	21
2242	03 April 2017	8	14.893	0	11.115	22

Table 23. Initial comparison of energy use of services of the case study

	Real data-from commercial farm	**Simulation Study**
TOTAL	**Monitored Data** **211,893** (kWh)	**SIM Data** **662,861** (kWh)

The 3 figures: **Heating/Cooling/Vent**, are ADDED to compare simulated results with the OVERALL ENERGY USE BY THE AHU (Air Handling Unit)

The finding described before (Table 23). Provided initial evidence of the nature of these values. The total energy consumption compared differed by a factor of 3, hypothesis about the reason behind the discrepancy of these total value can be:

1. Due to the fact that several assumptions were made for the purpose of this research with regards to some of the parameters (i.e., construction materials of the host building, etc). It is therefore expected that these assumptions will result on a significant difference between the monitored vs the simulated parameters.
2. The fact that the difference of the total figures was exactly a factor of 3 (Table 23), i.e., 211,893 kWh monitored data vs 662,861 kWh simulated, can potentially be the results that the simulated data included measurements for 3 types of services (cooling, heating, and ventilation). Hence, further investigation in this area followed.

As a result of the findings above, further queries took place into the exploration of these values. One particular graph that provided useful insights of the data can be seen in Figure 62.

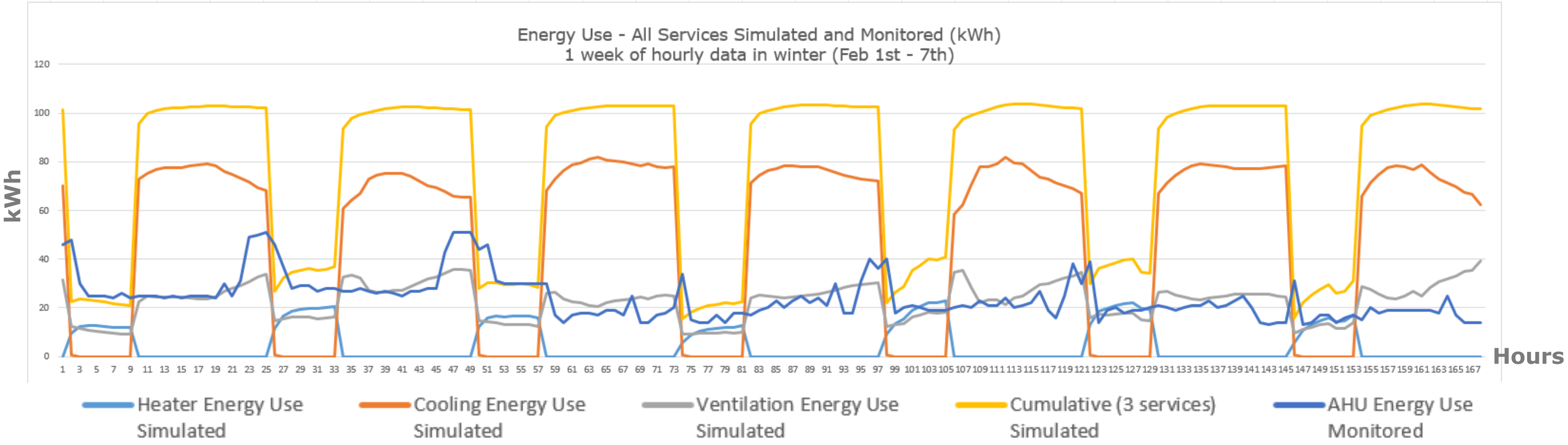


Figure 62. One week sample data for all the services. Comparing simulation vs monitored

In Figure 62, the total added value for all the services calculated in the simulation can be seen as yellow (cooling, heating and ventilation). Initially, as part of this investigation, it was expected that this total figure would be comparable to the energy used by the air handling unit of the monitored vertical farm (AHU: dark blue line). This was expected due to the information gathered from the case study. The AHU controls the temperature and humidity of the farm; therefore, it was assumed in this research that the AHU provided the necessary cooling and heating though the ventilation system to maintain the indoor environment at the optimum/desired levels. Figure 62 however reveals that the monitored value of the energy consumption from the AHU can be more closely compared to the ventilation values from the simulation (grey line), rather than the accumulated value (yellow line).

Hence, it has been concluded that the monitored data can also be further populated with data specifying values for energy consumption used for cooling and heating, if data is available. From Figure 62, it can be seen that the ventilation values from the simulation model, follow a similar pattern and similar rate as the monitored values. Therefore, this can prove to be a valuable tool to further explore this relationship and potential to simulate these important figures in advance.

- Lighting:

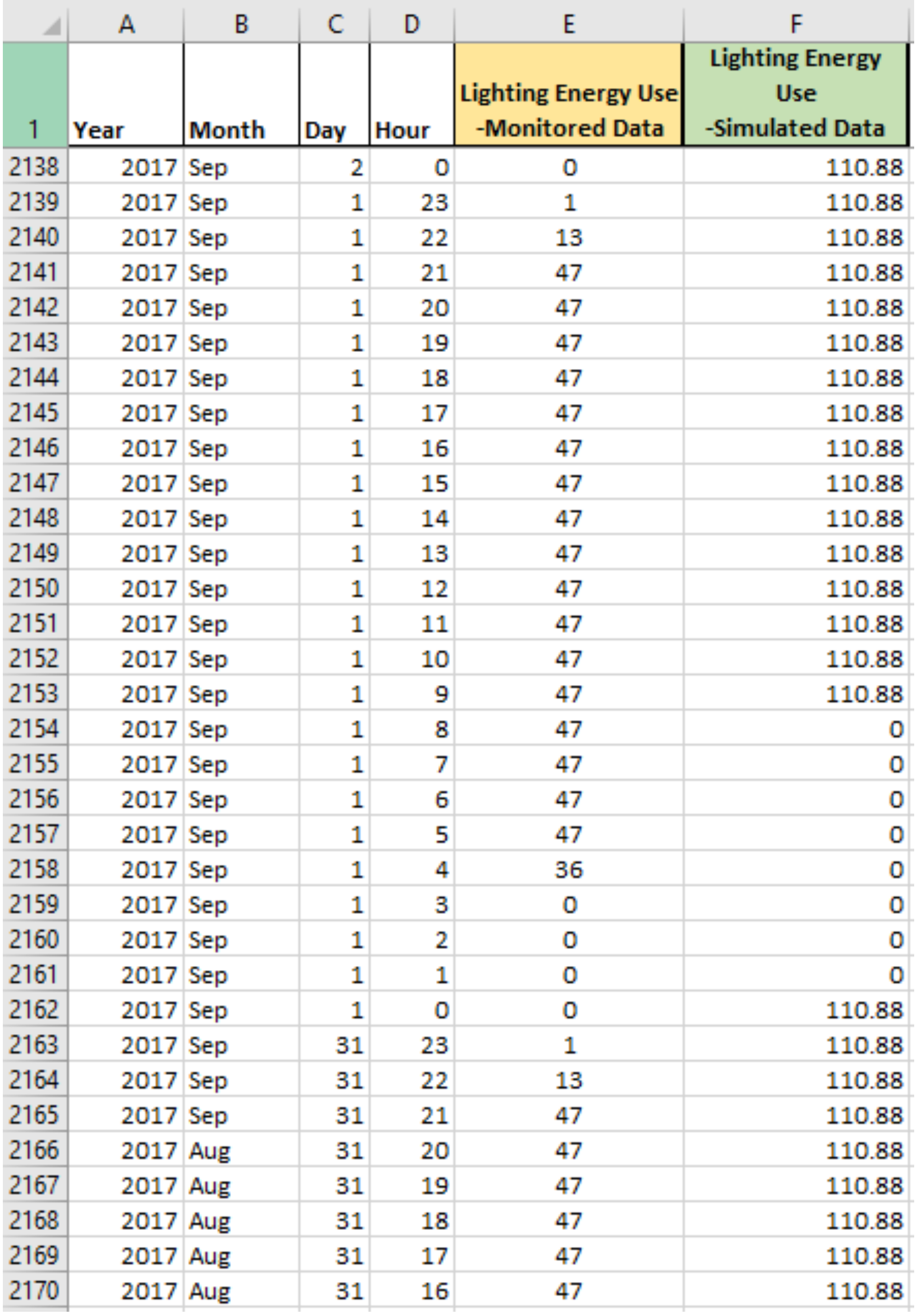
Lighting is one of the most challenging aspects of vertical farms (Kozai et al. 2016a; Kalantari et al. 2017a; Molin and Martin 2018a). Therefore, the potential to be able to simulate and predict the energy consumption of a vertical farm in advance can significantly empower new projects, to be able to plan ahead their designs. The framework proposed in chapter 5 allows for the exploration of this aspect also. Table 24 provides a snapshot of the lighting database developed for this case study, comparing simulated vs monitored data. The data was queried, and the overall total figures calculated are included in Table 25.

The lighting data is highly influenced by the nature of the requirements to meet the needs of plants. Vertical farms divide the schedule into photoperiod and darkperiod, and these are shaped by the plants need of light for their photosynthesis process. In order to maximise the capabilities of simulating this environment, the analysis takes under consideration in particular the characteristics below:

Parameter	**Unit**
Lighting Energy Use	kWh
Lights ON (photoperiod)	Number of benches ON (grow trays)
Lights OFF (darkperiod)	Number of benches OFF (grow trays)

Hence, the total values calculated (outlined in Table 25), showed a difference close to a factor of 2, between the monitored and the simulated data, for this case study. This has been a positive outcome for this investigation, due to the fact that, because of the complexity of the case study, the simulation assumed all lights to be ON during the photoperiod, whilst in reality, the monitored data reflect that not all lights were ON in this manner, as lighting is used according to the number of plants that require it, i.e., the farms doesn’t always run at full capacity.

Table 24. Lighting Energy Use Data (kWh):
Comparing simulated (HTB2) vs monitored data (GrowUp Farm).
The full table contains hourly data for the whole year.



	A	B	C	D	E	F
1	Year	Month	Day	Hour	Lighting Energy Use -Monitored Data	Lighting Energy Use -Simulated Data
2138	2017	Sep	2	0	0	110.88
2139	2017	Sep	1	23	1	110.88
2140	2017	Sep	1	22	13	110.88
2141	2017	Sep	1	21	47	110.88
2142	2017	Sep	1	20	47	110.88
2143	2017	Sep	1	19	47	110.88
2144	2017	Sep	1	18	47	110.88
2145	2017	Sep	1	17	47	110.88
2146	2017	Sep	1	16	47	110.88
2147	2017	Sep	1	15	47	110.88
2148	2017	Sep	1	14	47	110.88
2149	2017	Sep	1	13	47	110.88
2150	2017	Sep	1	12	47	110.88
2151	2017	Sep	1	11	47	110.88
2152	2017	Sep	1	10	47	110.88
2153	2017	Sep	1	9	47	110.88
2154	2017	Sep	1	8	47	0
2155	2017	Sep	1	7	47	0
2156	2017	Sep	1	6	47	0
2157	2017	Sep	1	5	47	0
2158	2017	Sep	1	4	36	0
2159	2017	Sep	1	3	0	0
2160	2017	Sep	1	2	0	0
2161	2017	Sep	1	1	0	0
2162	2017	Sep	1	0	0	110.88
2163	2017	Sep	31	23	1	110.88
2164	2017	Sep	31	22	13	110.88
2165	2017	Sep	31	21	47	110.88
2166	2017	Aug	31	20	47	110.88
2167	2017	Aug	31	19	47	110.88
2168	2017	Aug	31	18	47	110.88
2169	2017	Aug	31	17	47	110.88
2170	2017	Aug	31	16	47	110.88

Table 25. Total figures of the comparative energy consumption of lighting: monitored vs simulated

	Real data-from commercial farm	**Simulation Study**
TOTAL	**Monitored Data** **306,713** (kWh)	**SIM Data** **652,751** (kWh)

Therefore, due to the difference described above, it was expected that the simulated figure was going to be significantly higher. In this case, it turns out to be double, which suggests that the simulation is overestimating the reality by assuming all lights are turned ON during all photoperiods. This outcome will be valuable to inform future development of this simulation framework, to allow the functionality to predict different levels of energy consumption, depending on full/medium/low capacity of lights ON.

Furthermore, the lighting data was also compared, in order to gather further evidence on how these parameters influence each other and the validity of approaching vertical farms in a holistic manner, and not on independent parameter basis. In order to test the validity of the outcomes of HTB2 regarding the lighting system, here is presented a comparison between the monitored data and the simulated data. Table 26 presents the descriptive statistics. It is observed that the maximum values for the monitored data was 52 kWh, while the maximum for the simulations was 111 kWh. Similarly, the sum of the consumption over the year was 304,736 kWh for the monitored against 652,75 kWh for the simulation.

Table 26. Descriptive statistics of the lighting energy use database (N 8831)

	Minimum	*Maximum*	*Sum*	*Mean*	*Std. Deviation*
Lighting energy use Monitored Data (kWh)	.0	52	304736	35	19
Lighting energy use Simulated Data (kWh)	.0	111	652751	74	52

The data provided by the monitored vertical farm include details about the number of benches that were on or off every hour. Contrariwise, HTB2 only allows to consider if the lamps are all on (energy use of 111 kWh) or all off (0 kWh). In order to be able to make any comparison with the monitored data, details about the percentage of lamps that were ON was explored further. Figure 63, presents the data distribution of the percentage of lamps ON. 16% of the time all the lamps were off and almost 60% of the time over 80% of the lamps were on.

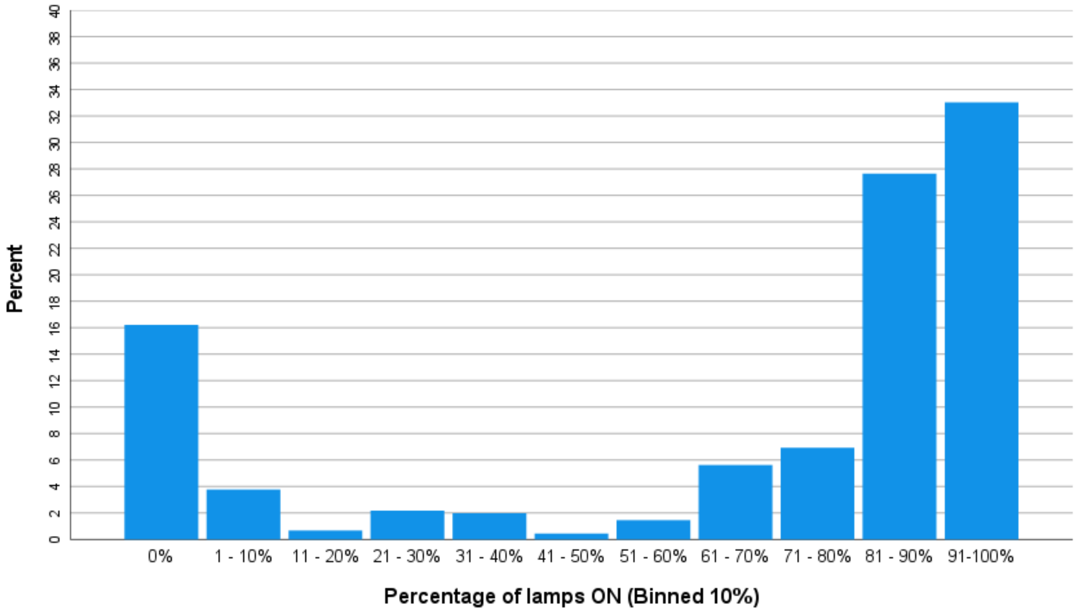


Figure 63. Percentage distribution of the monitored data - percentage of lamps ON binned at 10%

To compare monitored and simulated data, two variables were calculated to assume low consume (0) and high consume (1). In the case of the monitored data, the percentage of lamps ON was filtered as equal or below to 50% for low consume, and over 50% percent as high consume. For the simulated data, the variable Lighting energy use simulated was filtered as 0 kWh equal to low consume and 111 kWh high consume. Table 27 present the frequency distribution of these dichotomous variables.

Table 27. Frequency distribution of low and high consumption

Frequency Low (0) and High (1) consumption

	Monitored Data		*Simulated Data*	
	Frequency	Percent	Frequency	Percent
Low (0)	2192	24.8	2944	33.3
High (1)	6476	73.3	5887	66.7
Missing	166	1.8	-	-
Total	8831	100	8831	100

Table 28 shows the comparison between the dichotomous variables, presenting the number of times the simulated data coincided with the monitored data. A coincidence was found of 52.9% of the data. Most of the coincidence occurred for the high consumption data (48.4%).

Table 28. Test of Coincidence and Difference between Monitored and Simulated datasets

Difference between datasets

	Frequency	*Percent*
Coincidence 0 (low consumption)	399	4.5
Coincidence 1 (high consumption)	4276	48.4
Different	3993	45.2
Missing	163	1.8
Total	8831	100

Further Weather Analysis

Final results of the simulation compared to the monitored data and the weather data was thereafter further queried and compared in order to understand the relationship between all these parameters.

- Temperature Seasonality

Further valuable date queries and analysis are shown in Figure 64, Figure 65 and Figure 66. These graphs provide insights of the relationship of the different parameters, here the influence of the outside temperature is compared to both monitored and simulated indoor temperature values. The graphs below provide representative data for a typical summer week (Figure 64), winter week (Figure 65) and a sample graph from a shoulder season (autumn, Figure 66).

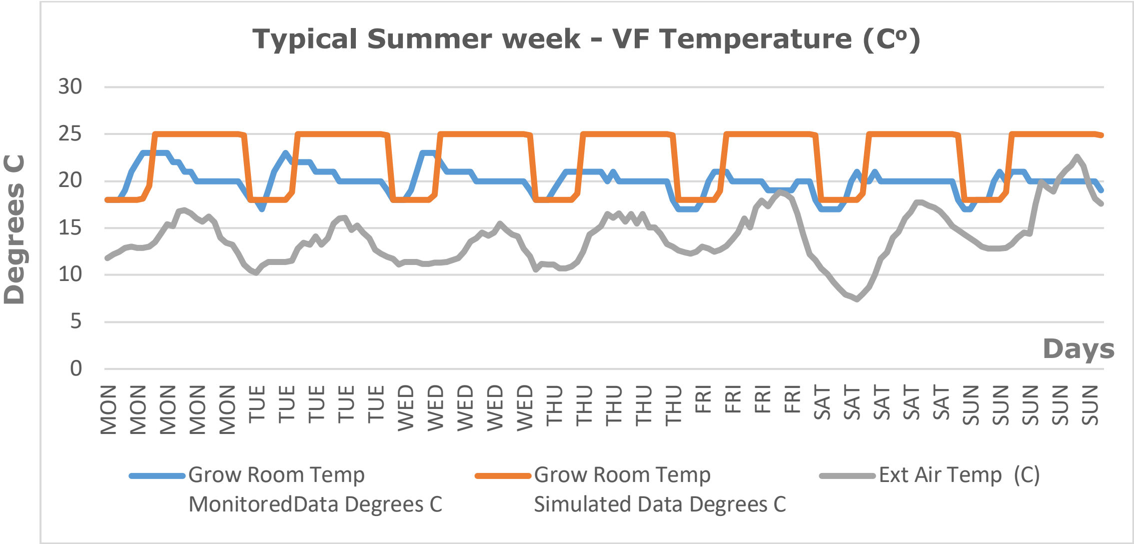


Figure 64. Typical week data comparing Simulation and Monitored data

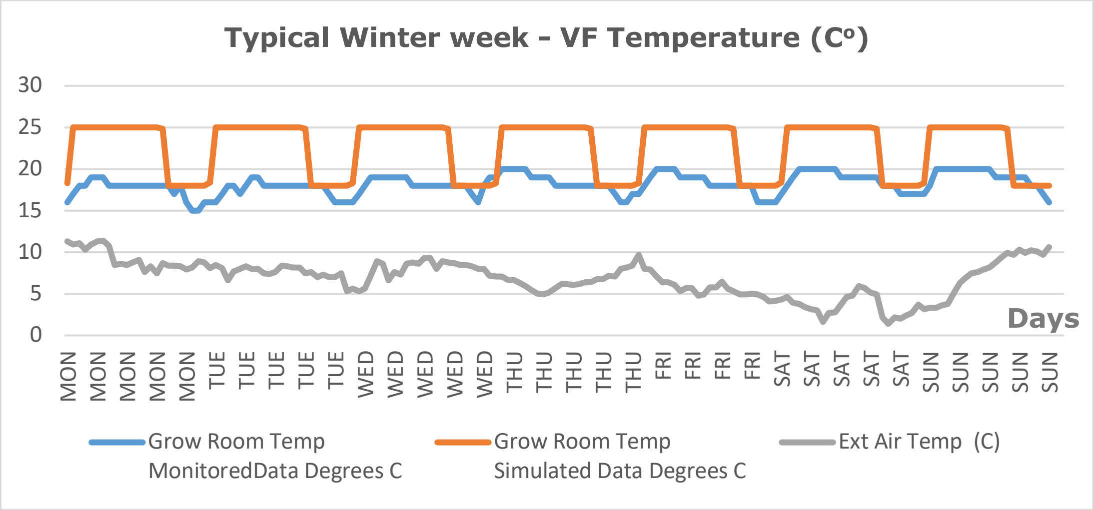


Figure 65. Typical week data comparing Simulation and Monitored data (Jan 2nd – 8th)

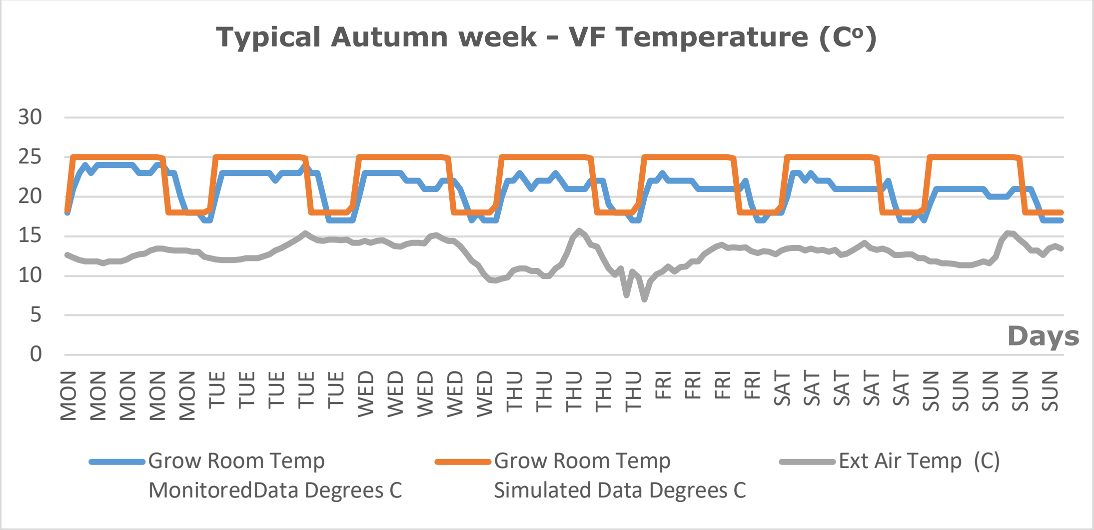


Figure 66. Typical week data comparing Simulation and Monitored data (Oct 17th - 23rd)

The graphs above show that although the simulated data is a lot more rigid than the monitored data, both datasets follow a similar pattern. Suggesting that this process has the potential to be optimised to recreate these scenarios more closely, i.e., the simulation has the potential to be improved for the purpose of early-stage prediction of the behaviour of the indoor temperature.

- Humidity Seasonality

Similar approach was thereafter followed to understand the datasets related to humidity of this case study, considering that this is another challenging parameter mentioned in the literature (Tsitsimpelis et al. 2016; Graamans et al. 2017). Figure 67, Figure 68, Figure 69 and Figure 70 are the sample data for one typical week for all the four seasons. The analysis of the datasets related to humidity data has a higher level of complexity, compared to the temperature capabilities of HTB2, since this specific characteristic of vertical farms have never been tested. From the outcomes below, it is believed that the simulation still requires a lot more details and improving of the process, to account for relative humidity inside vertical farms.

Note in the graphs below, that the behaviour of the simulated data (orange line) does not relate to the behaviour of the monitored data (blue line). The monitored data presents more stability, whilst the simulated data fluctuates significantly, much like the behaviour of the relative humidity outdoors, from the weather data (grey line). This difference in pattern between monitored and simulated relative humidity data can be due to several reasons, one suitable possibility is that the ventilation system of the case study runs a humidity control system, but details on this were not provided. An alternative option is the issue around the accuracy of the tool to recreate the behaviour of the plants in full, the occupancy module of HTB2 still requires further detailed development. This is the first attempt to manipulate HTB2 to consider the impact of plants inside buildings, therefore, it is recommended that these results are considered for further studies to exploit the capabilities of HTB2.

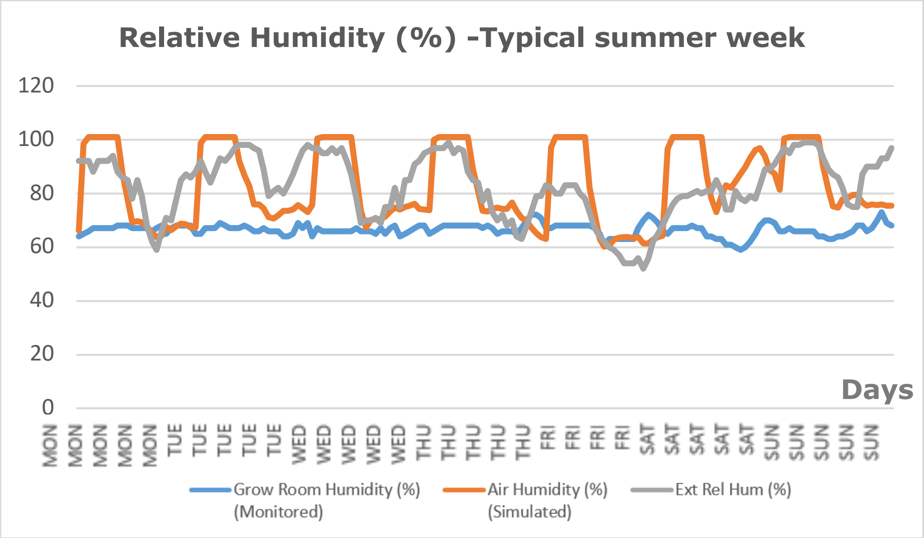


Figure 67. Typical summer week data relative humidity (June 1st – 7th)

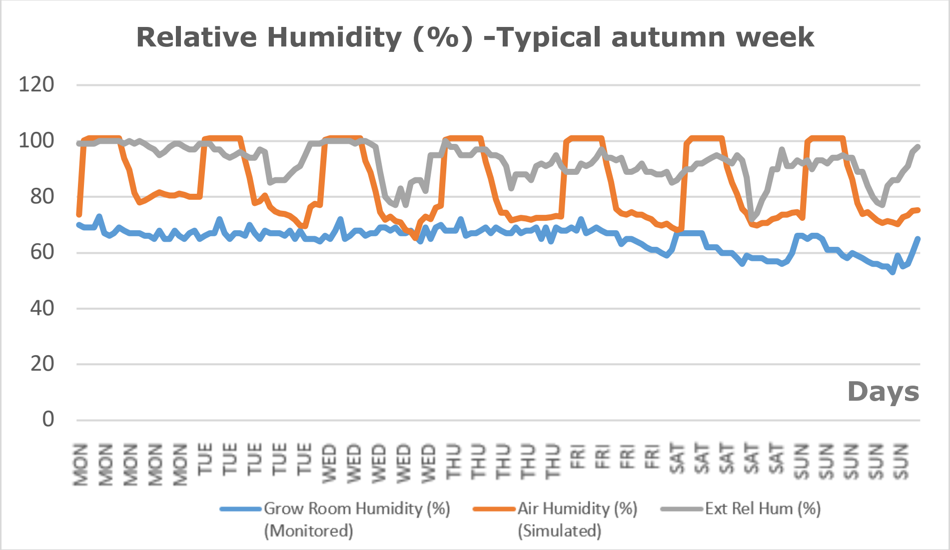


Figure 68. Typical autumn week data relative humidity (Oct 17th - 23rd)

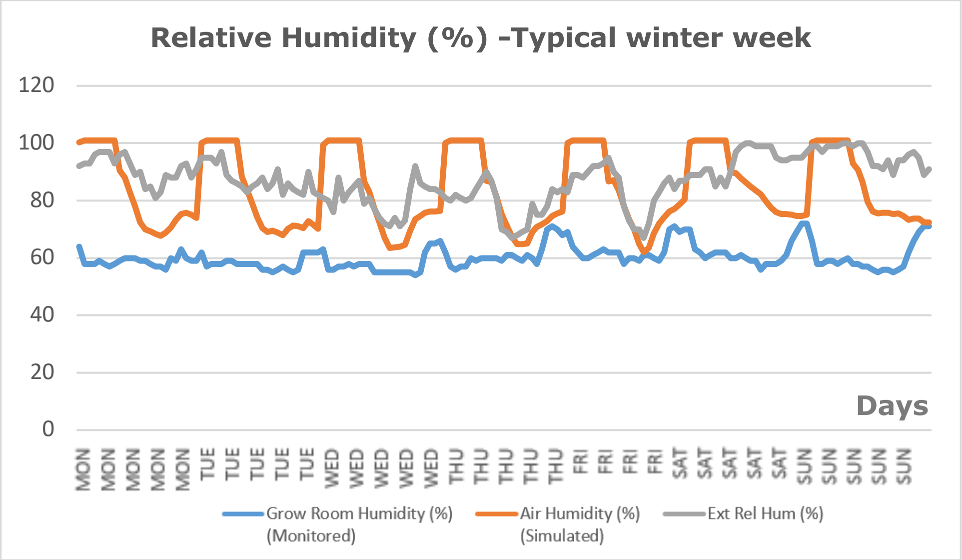


Figure 69. Typical winter week data relative humidity (Feb 1st – 7th)

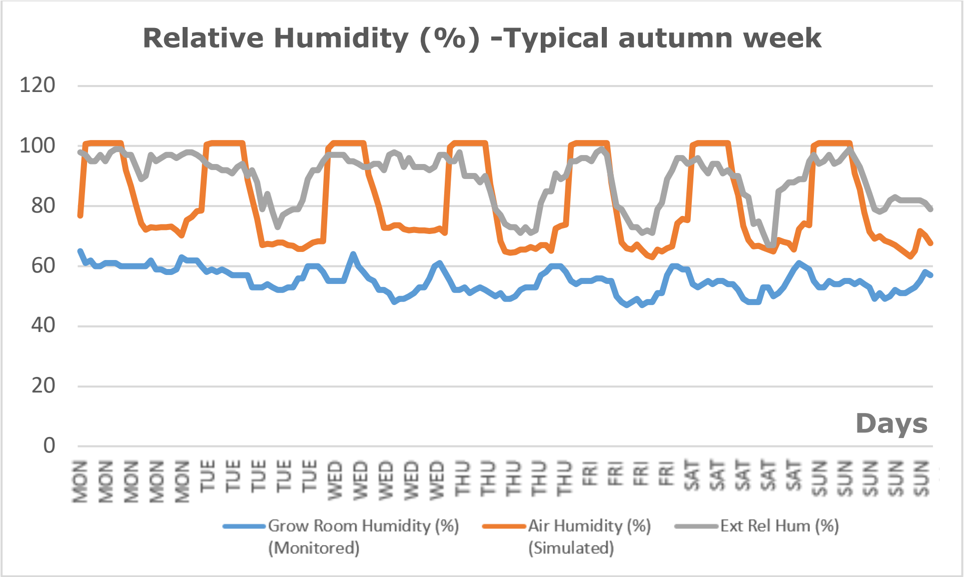


Figure 70. Typical spring week data relative humidity (April 15th – 21st)

Part of the further analysis that took place to learn more insights into this dataset was also to make a comparative analysis of hourly data of a whole month, representative for each season. The main aim was to observe these parameters in a more holistic manner, where the monthly parameters can hold particular clues of knowledge for the further development of HTB2 as a potential tool for vertical farming simulation. From the large comparative graphs presented in Figure 71, it can be observed that the monitored relative humidity (RH) data seems to be more independent during the winter season only. Spring, autumn, and summer monitored RH seem to be much closer to the outside weather. This can potentially suggest that less energy could be spent in regulating RH levels during the three seasons that the needs of the vertical farm stand at similar levels to the outside. There is also potential for further research in this area.

HTB2 accounts for the water counter balance and humidity present in the air (Alexander 2008). Therefore, this investigation continues to reiterate the holistic approach, by using HTB2 the influence of the outside weather is included in the calculations for vertical farming predictions, allowing to calculate dew points which is helpful data to develop a humidity management schedule for a specific scenario. This information has the potential to be exploited in further research to plan for the use of condense water system integrating it to the hydroponics system, or watering system integrated in the vertical farm. This can therefore constitute a sustainable source of water, besides the commonly acknowledge rainwater harvesting (ref), the water from condensation can also be integrated in the design of future vertical farms.

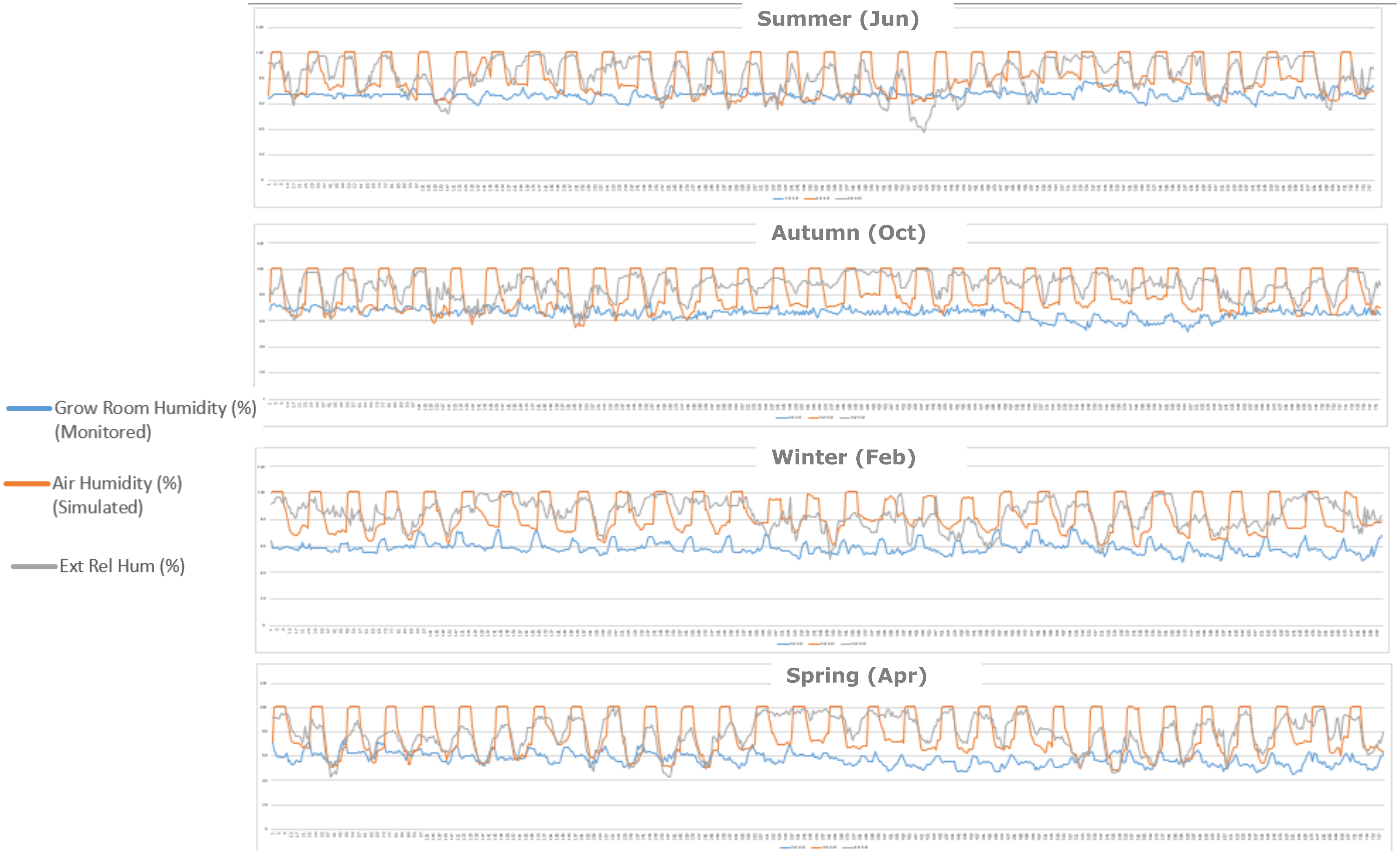


Figure 71. Hourly data for one month for each season. The horizontal (x) axis are the numbers of hours for each day of the month (30/31 days) and the vertical (Y) axis is the RH (%)

6.5 Limitations

Availability of data: Even when enthusiastic collaborators are found eager to share data and information (whom can also be rare in this industry), sometimes they do not possess all the necessary details to follow the proposed framework. Therefore, contingency plans must be put in place for these situations and plans for necessary assumptions that can be used to appraise assumptions that will not compromise the results and can help with the closer recreation of the scenario. Learning from this case study, it was difficult to obtain the specific construction details for the buildings, which was a rented commercial location. Therefore, the more populated the "user library" of construction materials can be for vertical farms, the more beneficial it will be for the vertical farming community. By having this library as an open source, the community can share this data and sample data can then be selected for similar scenarios.

6.6 Chapter summary

In this chapter, the selection process of the active and commercial vertical farm-case study has been described. The characteristics drawn from the commercial case study were then used to develop the simulated version of this vertical farm, by following the framework developed in the previous Chapter 5. The chapter provides details of this process, keeping in mind that the reader of this work can replicate this process if/when needed, to analyse any vertical farm(s). Finally, information on the type of analysis undertaken with the data was included, such as the comparison of relevant parameters such as temperature and relative humidity of both scenarios (monitored vs simulated). This chapter also includes the statistical analysis and findings of this data, which was undertaken with the aim of assessing how closely related the two sets of data are. It has been shown that there is a high correlation between several of the parameters analysed during this investigation.

Chapter 7
General Discussion and Conclusions

"Knowledge is the only acquired asset that will be with you wherever you go. It will give you freedom and the power to have a positive impact, to help others and to make this a better world".

Alicia Maria Toro E. BSc
My Mum

7.1. Chapter Overview

This chapter presents a general discussion and overview of the most relevant findings regarding the holistic approach undertaken to develop a simulation framework to recreate at design stage a vertical farm, making use of an open-source tool and taking into account multiple factors, some of them not previously accounted for in vertical farm simulations.

7.2. Discussion of research findings

This section summarises the discussion around the findings of this research work. An interesting statistic mentioned in the literature review chapter seems particularly relevant to highlight in this closing chapter again, in light of the outcomes of this research. Bearing in mind that Japan is one of the countries that has invested more time and money in the development of vertical farms (see time-line in Chapter 2), in one of his most recent publications, the prominent Japanese author, Dr Kozai published that it was found that the number of plant factories in Japan making profit increased from 25% to 50% between 2016 and 2019 (Kozai et al. 2016b, 2019) indicating the benefit achievable. These figures reflect the potential possibilities to improve the efficiency of this industry, the economies of scale can certainly help to drive the cost of vertical farms down and there is a significant need to conduct further studies in this field. This thesis argues the case of the relevance of multidisciplinary and transparent collaboration, in order to achieve more in the area of vertical farms, plant factories and related disciplines. The research findings below can provide steppingstones in this direction of research for this field.

7.2.1. Contribution to the holistic approach to the concept of vertical farms, multidisciplinary data-sharing and concept of a simulation-based framework

As expressed by Higgins (2016), there are still a lot of unanswered questions in the world of vertical farming. This statement is echoed by Khan and Ahmed (2017), Avgoustaki and Xydis (2020) and Storey et al. (2020), to mention but a few.

Specifically, some of the most popular unanswered questions that are highlighted in the published work related to vertical farms have been signposted throughout the body of this thesis. In brief, the most common topics being:

- How can the cost of lighting be reduced to make vertical farming more financially viable? (Kozai 2014; Mitchell and Sheibani 2015; Higgins 2016). The development of LED lights has not been enough, the energy consumption attached to lighting, requires better management, planning and higher efficiency.
- Why is there such a high number of commercial vertical farms that struggle to survive? Is the current busines model sustainable? (Higgins 2016; Kalantari et al. 2017b; Martin and Molin 2019). What can be learned from the examples set by Japan as well as other successful vertical farm stories?
- How can we make detailed knowledge of vertical farms more widely available? Aiming to achieve higher levels of

understanding across different areas of expertise, in order to better understand how each of the relevant factors affecting the overall efficiency of vertical farms influence each other? And how can these factors be brought together, in a holistic manner, to make this agricultural practice more environmentally sustainable, as well as economically viable? (Safikhani et al. 2014; Higgins 2016)

- How can collaboration, transparency and multidisciplinary alliances be encouraged and achieved, within the world of vertical farms? (Despommier 2010; Al-Kodmany 2018; Shamshiri et al. 2018; Storey et al. 2020; Zimmerman-Loessl et al. 2020)
- How can the overall affordability of vertical farms be achieved? (Shao et al. 2016; Hughes 2018; Avgoustaki and Xydis 2020)

With the development of the framework described in chapter 5 and tested in chapter 6, it has been demonstrated that this is an open-access method which relevant disciplines can use to further develop the simulation aspect of vertical farms. The main part of the framework is assisted by a software tool that is flexible enough to allow different disciplines to focus on their specific expertise. The supporting software is free, open-source, and accessible to the research community. The name of the software is HTB2 (Alexander and Lewis 1985; Lewis and Alexander 1990). This software was initially developed to perform building physics calculations and it has been further developed throughout the years (Lomas 1996; Waldron et al. 2013; Huang et al. 2020).

7.2.2. Contribution on a novel approach to simulation of vertical farms.

This PhD thesis is the first attempt to use HTB2 as an assistive tool to the framework developed for the appraisal and early-stage design of vertical farms proposed in this investigation. Nevertheless, this software tool has been previously validated within other contexts. The most valuable characteristic that this framework aimed to exploit from HTB2 is its flexibility, which encourages further research and development in multifaceted and multidisciplinary fields. Therefore, this thesis presents the process of how these characteristics are being integrated in the design of vertical farms, allowing to simulate scenarios as early as the conception stage of the design process. Due to the flexible nature of the simulation tool chosen to assist this process, the framework presented in this investigation can empower the vertical farming world to tackle the design of these projects in a multidisciplinary manner, in order to allow different experts to focus on their relevant topic, whilst collaborating in the development of any type of vertical farm.

For example, experts in the area of lighting can learn more specifically the necessary routines that are currently included in the lighting “module” of the simulation software (HTB2). These experts can take ownership of this field and further develop it to include any number of variables that can be present in vertical farms. By exploiting the current capabilities of the tool and further exploring and developing these areas, the experts involved in this process can integrate their knowledge into the tool itself. Thereafter, their particular “module” (focused on lighting, in this example) can then be linked to other “modules” of HTB2, that comprise details about other relevant areas of vertical farms. In parallel, other experts in the field of biology, or evapotranspiration of plants, or any related topics, can follow the same process, focused on their area of expertise, knowing that this knowledge will be linked to the overall structure. All these modules are then interlinked by using HTB2, which at the moment is limited in what can achieved for vertical farms, but as a tool, it has potential for further research and development in the field of vertical farms.

Overall, the framework described in this thesis empowers different disciplines involved in vertical farms to communicate details and parameters in a transparent manner. The various elements of vertical farms are catalogued in a series of files, each of them describing all the details of the case study and each of these files can be openly shared. These files contain the information that is needed to allow the designer of a vertical farm to use HTB2 to perform early stage predicted calculations and estimations for the energy consumption of the farm and other parameters. More importantly however, designers can compare details between different scenarios in order to aim for optimisation, and in turn, databases can be created. All this information can thereafter be shared and compared in a consistent manner, across the international vertical farming community.

By creating more databases with this structured form of information, the framework can be further improved and optimised in order to get closer to recreating all the parameters of vertical farms more accurately. Following this process, with more detailed data and information, this framework can thereafter be validated with existing vertical farms, checking if the calculations are accurate in terms of predicting energy usage of lighting, ventilation, temperature, and humidity levels, among others. Since one of the most significant obstacles of building vertical farms is the high initial investment, validating a framework that can estimate potential energy usage before they are built, can prove to be a valuable tool to assist vertical farming developments.

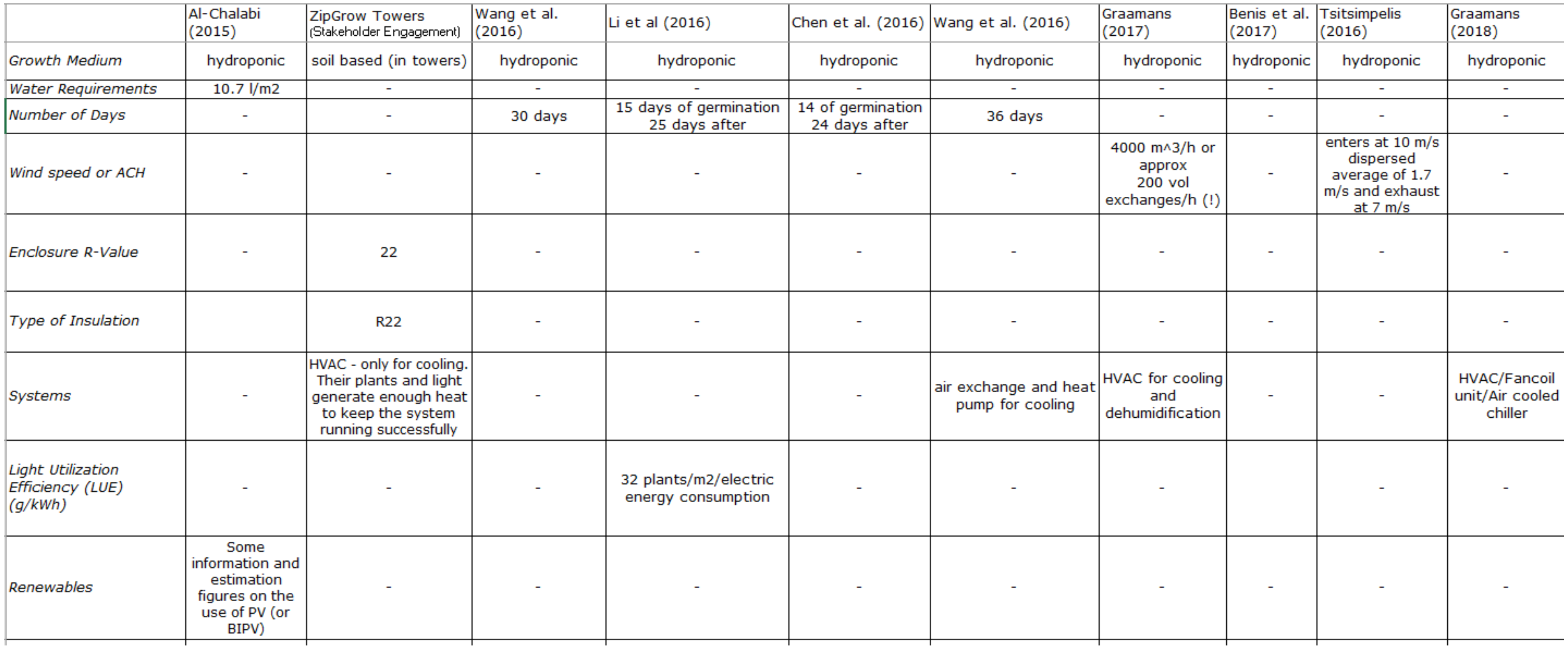
7.2.3. Contribution to the calculation of parameters relevant to the analysis of vertical farms.

Due to the novel perspective of approaching the issues around the design of vertical farms, there have been a number of parameters that have been highlighted in this research work.

Table 29 is a section of a larger table presented in chapter 5 (Table 10). The larger table presented a summary of relevant parameters found in the literature that are relevant for the analysis of vertical farms. The section of the table inserted below aims to bring focus to the fact that there are significant gaps in the literature of vertical farms (and related building integrated agricultural concepts, i.e. plant factories). The fields or parameters presented in the excerpt of the table are related to:

- ventilation rate of vertical farms (wind speed or ACH).
- R-value (or u-value) of the host building (occasionally described as “enclosure” in the literature).
- Type of insulation of the host building.
- Lighting efficiency.
- Renewable energy.

At present, table 29 continues to have many gaps, because a standardised manner to report the characteristics of vertical farms does not exist. If move forward, in the future, this simulation framework can provide all the data that would be necessary to fill table 29, making it more transparent for vertical farms to learn from each other and improve practices. The next section will provide more details on this matter (section 7.2.4).



	Al-Chalabi (2015)	ZipGrow Towers (Stakeholder Engagement)	Wang et al. (2016)	Li et al (2016)	Chen et al. (2016)	Wang et al. (2016)	Graamans (2017)	Benis et al. (2017)	Tsitsimpelis (2016)	Graamans (2018)
Growth Medium	hydroponic	soil based (in towers)	hydroponic	hydroponic	hydroponic	hydroponic	hydroponic	hydroponic	hydroponic	hydroponic
Water Requirements	10.7 l/m2	-	-	-	-	-	-	-	-	-
Number of Days	-	-	30 days	15 days of germination 25 days after	14 of germination 24 days after	36 days	-	-	-	-
Wind speed or ACH	-	-	-	-	-	-	4000 m^3/h or approx 200 vol exchanges/h (!)	-	enters at 10 m/s dispersed average of 1.7 m/s and exhaust at 7 m/s	-
Enclosure R-Value	-	22	-	-	-	-	-	-	-	-
Type of Insulation		R22	-	-	-	-	-	-	-	-
Systems	-	HVAC - only for cooling. Their plants and light generate enough heat to keep the system running successfully	-	-	-	air exchange and heat pump for cooling	HVAC for cooling and dehumidification	-	-	HVAC/Fancoil unit/Air cooled chiller
Light Utilization Efficiency (LUE) (g/kWh)	-	-	-	32 plants/m2/electric energy consumption	-	-	-		-	-
Renewables	Some information and estimation figures on the use of PV (or BIPV)	-	-	-	-	-	-	-	-	-

Table 29. (Excerpt of Table 10-Chapter 4) “Parameters for simulation gatahered from literature review, plus other relevant data within the context of vertical farming”.

7.2.4. Filling the table's gaps (in the literature)

Throughout the development of the framework described in chapter 5, the simulation methodology outlines the importance of establishing the thermal properties of the construction materials of a host building to assess the thermal performance of vertical farms. Therefore, by implementing the assessment analysis proposed by this research, vertical farms will include this information as part of the design process. Furthermore, data such as the r- or u-value of the host building, type of insulation and lighting efficiency will be available for every vertical farming projects to share, by following the framework proposed in this investigation.

At present, there is no evidence of which type of construction materials can be best suited for vertical farms. As part of this investigation a "user library" was created containing an initial list of building materials to use for vertical farms (chapter 5, section 5.5.1.3 and figure 28). The aim is to share this library with the vertical farming community in order to populate it further. The library contains thermal properties of the materials, such as conductivity (W/m/C), density (kg/m3) and specific heat capacity (J/kg/C), allowing the software (HTB2) to calculate u-values. Any construction material can be integrated into this software tool, as long as the three parameters mentioned above are available.

7.2.5. Contribution on relationship of different parameters

This research provides evidence on the correlation amongst the various parameters relevant for the analysis of vertical farms. The statistical analysis described in chapter 6 shows the results of the monitored data of an active vertical farm where a direct correlation was identified between the outside weather and the indoor parameters. The relationship between the outside and the inside environment was evidenced with the correlations between the outside temperature and the energy used by the air handling unit (AHU) ($r = .403, p < .05$), grow room temperature ($r = .398, p < .05$) and grow room humidity ($r = .348, p < .05$). This evidence contradicts common assumptions by vertical farming publications which consider the outside temperature as a negligible factor when assessing the efficiency of vertical farms (Kozai et al. 2016b; Al-Kodmany 2018). A very small amount of publications actually include details of the weather to assess a vertical farm (Benis et al. 2017a; Graamans et al. 2018).

Furthermore, the statistical analysis also confirmed that the highest correlation for the total energy use was with the variables related to lighting energy use (r = .63, p < .05). See further details of the correlation of the monitored data in chapter 6, section 6.4.2 and Table 20.

7.2.6. Contribution on lighting analysis

Due to the importance of the impact of lighting in the further development of vertical farms (Mitchell and Sheibani 2015; Li et al. 2016; Molin and Martin 2018b), additional statistical analysis took place in this area (see Table 20 and attached information, in Chapter 6). The analysis compared the results of the simulation and the monitored data from the commercial case study. The nature of the lighting data is mainly split into two scenarios for vertical farms: photoperiod and darkperiod, i.e., ON and OFF. Therefore, if these are established as the main dichotomous variables, then further comparisons between the simulated data can be achieved. Therefore, beyond being able to calculate and compare the energy consumption of light between simulation and monitored data, this statistical analysis allowed to identify a percentage of coincidence between the dichotomous variables, i.e., coincidences of the prediction of lights ON or OFF. The coincidence percentage found was 52.9% of the data. Most of the coincidence occurred for the high consumption data (48.4%). Therefore, 48% of the time the simulation and the monitored data agreed on lights ON. The above information highlights the relevance of the work undertaken as part of the framework developed in this thesis, that can be used as a foundation to build further lighting analysis and predictions of vertical farms. This can further inform lighting management prediction strategies.

7.2.7. Contribution on analysis of simultaneous parameters

The analysis of the graphs presenting the behaviour of the internal temperature and relative humidity in relation to the outside weather (Figures 64 to 71, in chapter 6), have significant information to contribute towards better indoor climate management strategies. This is another gap of vertical farms highlighted by Higgins (2016). In the outcomes of this research, the evidence presented in Figure 71 of Chapter 6, suggests that internal relative humidity can be better managed by considering the conditions of the outside weather. For instance, in this case the data suggested that the relative humidity indoors follows a similar pattern to the outside relative humidity for the majority of the months (the graph shows hourly data for 1 typical month for each season). Nevertheless, if observed in more detail, the winter month (Feb) seems to be the exception, i.e. the outside humidity differs most notably from the indoors conditions. The other three months (representing the remaining seasons: spring, summer and autumn) showed a similar level of relative humidity to the outside (Figure 71, Chapter 6). Hence, by considering this data in coordination with other data (without neglecting the inclusion of CO_2 levels), attention could be placed into the design of a by-pass scenario, to aim for energy saving measures from the air handling unit. In effect, if the data collected with this analysis suggests that the outside relative humidity is similar to the levels of humidity required by the crops, vertical farms that use air-conditioned environments, could improve the efficiency of their systems by having a by-pass mode, to be activated when the conditions of the outside air match the desired conditions for the crops.

7.2.8. Contribution towards potential renewable energy exploration

By using HTB2 as the assisting software tool for this framework, a further valuable characteristic can be explored: HTB2 has been used in previous studies for solar energy potential (Bassett et al. 2012). Hence, this is an area that can significantly benefit vertical farms. An exploratory sample of this analysis was included in this investigation in “Trial 5” of chapter 5 (see

Figure 47). Although it requires further development, this can be an initial steppingstone to improve this characteristic further in this context. Several publications mentioned the benefit of coupling vertical farms with renewable sources of energy (Kalantari et al. 2017a; Benis and Ferrão 2018; Kosorić et al. 2019; Tablada et al. 2020), but very few provided a solution on the best way to achieve this. Proksch et al. (2019) agrees with various authors on the potential of PV panels to reduce energy consumption of indoor faming, his publication cited the case of a high-tech greenhouse in Australia which is 50% supply from PV panels. Other authors who highlighted the benefit of integrating renewable energy in vertical farms are (Kosorić et al. 2019; Tablada et al. 2020) as well as other researchers highlighting the various potential of including PV panels in the built environment (Huovila et al. 2007; Parra et al. 2014; Coma Bassas et al. 2020). Whilst the exploration of the integration of PV potential is relevant, it must be taken under consideration the various relevant aspect toa chieve higher efficiency of PV panels. For example, in large cities, the potential to integrate PV panels on the facades of tall buildings instead of roofs is appealing (i.e. BIPV). Nevertheless, the orientation, inclination of panels and direct access to the sun have a significant impact on the efficiency of every single PV panel. This are careful considerations that need to be evaluated for each individual case scenario. An added value of using HTB2 for this simulating framework for vertical farms is that this software has been validated to undertake this kind of sensitivity analysis of potential efficiencies of PV panels.

7.3. Novel contribution to knowledge

The outcomes of this research contribute to improve the current methods to assess vertical farming buildings. By having a standardised framework, different vertical farms across the world can be compared and new efficiency benchmarks can be developed, encouraging multidisciplinary collaboration and transparent data-sharing.

This investigation aimed to deliver a step change in:

I. The development of a novel analytical and conceptual framework supported by simulation (based on HTB2), to appraise the viability of vertical farming buildings at an early stage of the design process. The area of simulation of vertical farms has very little development and there are no open-source freely available tools to undertake this analysis. This is one of the main gaps this investigation tackled.

II. This framework has the potential to allow future vertical farms designs to be optimised before they are built. This results in the tacit contribution to better and more energy-efficient vertical farms being deployed in the future, by using this framework to forecast different scenarios of energy consumption and assessing the possibility to be complemented by renewable energy.

7.4. Limitations

Literature review

The most significant limitation found in the literature is the lack of detailed data related to the design of vertical farms. In particular data that can be used to assess and/or simulate the different scenarios. Most available published data provides information about optimum temperature ranges, relative humidity or lighting hours (photoperiod), (Li et al. 2016; Wang et al. 2016; Benis et al. 2017a; Graamans et al. 2017; Graamans et al. 2018). However, finding details with regards to the optimum level of ventilation (ACH) or the thermal properties of the host building (u-values) has been particularly challenging, only Graamans et al. (2018) provided some details on u-values and ventilation. Furthermore, publications by Benis et al (2017, 2018) and Tsitsimpelis et al (2016) make some reference to these factors, but no specific details are provided, and the few details presented in terms of ventilation, for example, differ significantly from each other. Hence, reliability and testing of data of this nature requires further scrutiny and investigation.

The issues mentioned above, are also particularly important in terms of the analysis of the relationship of building materials interacting with indoor plants. Due to the high levels of humidity and other parameters highly relevant for an optimum indoor environment for plants and people, further research is recommend in the area of optimum building materials within this context. For example, further information on the use of hygroscopic materials (Tenwolde and Pilon 2007; Kalantari et al. 2017a) in the context of vertical farms could have significant potential to develop better performing urban farms.

Methodology

Groat & Wang (2013) wisely described the boundaries between different research strategies as "permeable", this characteristic was perhaps the most exciting about this research project, as well as the most challenging and, in occasions, overwhelming. This permeability between the different research methods chosen in this mixed-methods approach was an extremely enriching research experience. The amount of knowledge gained during the journey has been unmeasurable. However, trying to keep the knowledge-gaining experiences within the straight path to achieve the main objectives, was a significant challenge. Like most research paths, there are ups and downs and this has been certainly an enriching journey, filled with joy and pain. It would have been beneficial to have an "impermeable" research strategy, that could assist to tackle the issues at hand in a more straight forward process. Nevertheless, creation would probably not materialise, without the excitement and the occasional pain. Hence, from this perspective, having such an interactive set of mixed-methods in an investigative project can be extremely valuable, but it can also have its limitations if the boundaries of research are difficult to maintain at a manageable level. Hence, when using a mixed-method approach, ensure a strategy to keep the boundaries in-check. As Groat & Wang (2013) also described, the aspects of one method can successfully augment the characteristics of the other interacting methods.

Framework simulation development

Benis et al (2015, 2017, 2018) and Graamans et al (2017, 2018, 2020) are the main authors that have contributed significantly to the field of the exploration of simulation potential of vertical farms. Nevertheless their focus have been on specific types of agricultural methods integrated in the built environment, i.e. greenhouses and lab-like plant factories. Due to the lack of open-source tools used and transparent information, it is difficult to scrutinise the simulation models and identify which aspect of their work can be directly linked to other scenarios of vertical farms. Furthermore, the simulation results published are based on virtual scenarios. Any published data based on active vertical farms are related to the analysis of monitored figures, not simulations (Ward R et al. 2018; Jans-Singh et al. 2019). No studies have been found to compare both scenarios: monitored vs simulated. This is a novel approach, therefore the main limitation in this respect is the lack of comparative published research to validate the chosen methodology and framework development.

Case studies

As highlighted by Despommier in (2014), purposely designed building integrated vertical farms only began to emerge years after his first book published in 1999 (Despommier 1999). This field is still at its infancy (Storey et al. 2020; Zimmerman-Loessl et al. 2020) and therefore availability of case studies to validate the simulation framework is a challenging task. In particular, to find case studies that will have monitored data. During the planning of this investigation, the route of gathering own monitored data was also explored. But the logistics of achieving this, in conjunction with arranging access to a vertical farm that would allow the collection of this data was also a sensitive and complex affair. Due to a thorough scoping study and significant amount of systematic stakeholder engagement, this investigation found a suitable case study, willing to share their monitored data. This was a relatively unique opportunity, but it took a significant amount of searching, at a national and international scale (this investigation even included a trip to China during the scoping study). Hence, it is important to highlight that significant time consideration must be allowed to find a suitable case study. Alternatively, a contingency plan can be put in place to plan for data collection alongside the development of the simulation model, to be able to create the comparative scenarios as demonstrated in this thesis.

7.5. Suggestion for future research

In terms of software development, this research strongly encourages further expansion of the software tool used as part of this analytical framework. Due to its modularity, HTB2 allows for further development that can be written primarily by computer programmers, in collaboration with a multidisciplinary team that can assist the development focused on vertical farms. It is an open-source code. As a result, if further calculations are deemed to be relevant for the simulation of vertical farms, HTB2 code can be made available to create plugins or alternative functions that could potentially help to improve this simulation. One instance could potentially be to develop a module to account for evapotranspiration of plants in more detail than the current HTB2 module allows. There are already mathematical models to calculate these characteristics, such as the Penman-Monteith equations or using the Vanthoor model, researchers have used this principle to include it in their calculations (Allen 2005; Benis et al. 2017a). A software developer could potentially write a "module" for HTB2, or modify some of the existing modules to include evapotranspiration characteristics, or other further modules that can enrich the simulation. Similarly, there could be additional models to calculate water, CO2 requirements, etc. HTB2 can also potentially be expanded and tailored to further vertical farms requirements, if there is available R&D time to invest in the tool and the analytical framework developed in this thesis.

7.6. Conclusion

The framework developed in this investigation can potentially be used as a standardised approach to assess vertical farms at an early design stage. By having this as a platform, the vertical farming community can develop potential benchmarks around the world in terms of energy efficiency and quality of produce. This tool can potentially help towards more transparent communication and data-sharing across different levels of the vertical farm stakeholders around the globe. These latter characteristics can potentially act as catalysts for more collaboration and therefore allowing larger multidisciplinary teams working together towards achieving greater efficiency and affordability of vertical farms.

7.6.1. Review of aim and objectives

This final section summarises how this study achieved the aims it was set to fulfil, describing the novel contributions to the field.

> ***The aim of this thesis is to explore the potential and required future development of a simulation-based modelling framework to meet the needs of vertical farming. The main target of this framework is to provide a replicable methodology that can be expanded to integrate further aspects of vertical farms. This is with the wider purpose of improving our understanding of the concept of vertical farms, bringing together the variety of theories that are attached to this industry. The investigation proposes an analytical and conceptual framework to test a quantitative approach (simulation) to advance the knowledge in the area of the design of vertical farms. The framework developed is assisted by an open-source software tool and encourages future multidisciplinary collaboration and data-sharing.***

This study developed an analytical framework to approach the assessment of vertical farms from a novel angle. This new method focused on the value of multidisciplinary collaboration and transparency of data-sharing. With this focus in mind, a pathway to encourage and allow this collaboration has been built, as one of the main outcomes of this research. In order to achieve this, a software tool was selected to materialise the concepts of the framework. HTB2 is the software tool that has been chosen to assist this investigation throughout the development of this framework.

The main <u>objectives</u> to achieve this aim are:

1. ***To review the State of the Art of vertical farming, the different methods used in this alternative agricultural practice and establish the most appropriate method(s) to be recreated through the simulation process and data analysis.***

This research developed a thorough systematic literature review to consider the vast majority of literature available in the area of vertical farms and related practices/designs. The systematic literature review was complemented by an extensive stakeholder engagement, targeted to gather information related to the main gaps identified in the literature. The search for these gaps played a particularly relevant role towards the development of the analytical framework. This is due to the fact that this framework required clarity of data, detailed information and material/knowledge related to a number of different disciplines. The knowledge gained during the journey across the scoping studies, literature review, stakeholder engagement and further analysis of information and data, helped to synthesise the understanding of vertical farms. As a result, clear information regarding the State of The Art of vertical farms, their different methods and characteristics have been included in the chapters of this thesis. This information has thoroughly informed the process of recreating and simulating the selected vertical farming scenarios.

2. ***To propose, develop and test a conceptual and analytical framework that can be used to recreate or modify the behaviour of vertical farms in indoor environments, with the assistance of a flexible simulation tool.***

Chapter 5 provides a clear description of the process followed to develop the conceptual and analytical framework to recreate, analyse and modify vertical farming scenarios. This has been achieved with the integration of a simulation software tool (HTB2) which has been previously validated for other simulation scenarios. This is the first attempt to utilise the various characteristics of this software within the context of vertical farm design.

3. ***To test the simulation framework developed in order to assess an active vertical farm (case study). Including the assessment of the framework to allow the prediction of important parameters relevant to establishing an optimum environment required for the building to host a vertical farm indoors.***

Finally, the study presented in chapter 6 outlines the process followed to implement the framework (described in chapter 5), using a real case study: a commercial vertical farm in London. The analysis describes how the monitored data was accessed (as a result of stakeholder engagement), interrogated (to assess suitability) and thereafter compared to data that was simulated based on a virtual scenario that was built as part of this investigation, to recreate the scenario of this particular commercial vertical farm. Important parameters were identified and evaluated by using the proposed framework, with the target of establishing the calculation required to assess the optimum characteristics for vertical farms to thrive in their host buildings.

References

Agritecture 2014. A timeline of Vertical Farming. Available at: https://agritecture.tumblr.com/post/49940828352/a-timeline-of-vertical-farming-by-jessica. [Accessed: 15 March 2017].

Agritecture 2020. Agritecture Designer. Available at: https://www.agritecture.com/designer [Accessed: 10 December 2020].

Ahern, J. et al. 2014. The concept of ecosystem services in adaptive urban planning and design: A framework for supporting innovation. *Landscape and Urban Planning* 125, pp. 254–259. doi: 10.1016/j.landurbplan.2014.01.020.

Akinwolemiwa, O.H. et al. 2018. Building community-driven vertical greening systems for people living on less than £1 a day: A case study in Nigeria. *Building and Environment* 131(December 2017), pp. 277–287. doi: 10.1016/j.buildenv.2018.01.022.

Akinwolemiwa, O.H. and Gwilliam, J. 2015. Evaluating the Impact of Vertical Greening Systems on Thermal Comfort in Low Income residences in Lagos, Nigeria. *Procedia Engineering* 118, pp. 420–433. doi: 10.1016/j.proeng.2015.08.443.

Al-Chalabi, M. 2015. Vertical farming: Skyscraper sustainability? *Sustainable Cities and Society* 18, pp. 74–77.

Al-Kodmany, K. 2018. The vertical farm: A review of developments and implications for the vertical city. *Buildings* 8(2). doi: 10.3390/buildings8020024.

Alexander, D. 2008. *HTB2: Heat Transfer in Buildings (Version2.1), User manual*. Welsh School of Architecture ed. Welsh School of Architecture.

Alexander, D. and Lewis, P. 1985. *HTB2 Technical Reference Manual*. Welsh School of Architecture ed. Welsh Scool of Architecture. Available at: http://u001.arch.cf.ac.uk/plugin/HTB2_tech_manual.pdf. [Accessed: 10 December 2016].

Alexandri, E. and Jones, P. 2008. Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. *Building and Environment* 43(4), pp. 480–493.

Allen, R. 2005. Penman-Monteith Equation. *Encyclopedia of Soils in the Environment* , pp. 180–188.

Almeer, J. et al. 2016. *Sustainability Certification for Indoor Urban and Vertical Farms Association for Vertical Farming*.

Andrews, K. 2013. Pasona Urban Farm by Kono Design. Available at: https://www.dezeen.com/2013/09/12/pasona-urban-farm-by-kono-designs/ [Accessed: 18 December 2016]

Antonelli, P. 2002. Le Corbusier (Charles-Édouard Jeanneret) Plans for Algiers and Barcelona and "cité-jardin verticale" (vertical garden city) drawing made during a lecture in Chicago November 27, 1935. In: McQuaid, M. ed. *Envisioning Architecture: Drawings from The Museum of Modern Art*. New York: The Museum of Modern Art, p. 86.

Arc Studio_ 2018. Portfolio. Available at: https://arcstudio.com.sg/projects/ [Accessed: 9 August 2018].

Asao, T. 2012. *Hydroponics - A Standard Methodology for Plant Biological Researches*. doi: 10.5772/2215.

Association for Vertical Farming 2016. AVF Map. Available at: https://vertical-farming.net/.

Autodesk Support 2016. Ecotect Analysis Discontinuation FAQ. Available at: https://knowledge.autodesk.com/search-result/caas/sfdcarticles/sfdcarticles/Ecotect-Analysis-Discontinuation-FAQ.html [Accessed: 23 November 2016].

Avgoustaki, D. and Xydis, G. 2020. Plant factories in the water-food-energy Nexus era: a systematic bibliographical review. *Food Security* 12(2), pp. 253–268. doi: 10.1007/s12571-019-01003-z.

Bacon, F. et al. 1627. *Sylva Sylvarum Or A Naturall Historie In Ten Centuries*. Rawley, W. ed. J.H.

Bailey, G.E. 1915. *Vertical Farming*. California: E. I. Du Pont de Nemours Powder Co. Wilmington, Delaware.

Banerjee, C. and Adenaeuer, L. 2014a. Up, Up and Away! The Economics of Vertical Farming. *Journal of Agricultural Studies* 2(1), p. 40.

Banerjee, C. and Adenaeuer, L. 2014b. Up, Up and Away! The Economics of Vertical Farming. *Journal of Agricultural Studies* 2(1), p. 40.

Banholzer, S. et al. 2014. Chapter 2: The Impact of Climate Change on Natural Disasters. In: Singh, A. and Zommers, Z. eds. *Reducing Disaster: Early Warning Systems For Climate Change*. Springer, pp. 21–50. doi: 10.1007/978-94-017-8598-3.

Basnet, B. and Bang, J. 2018. The State-of-the-Art of Knowledge-Intensive Agriculture : A Review on Applied Sensing Systems and Data Analytics. *Journal of Sensors* 2018, p. 13. doi: 10.1155/2018/7425720.

Bassett, T. et al. 2012. Calculating the solar potential of the urban fabric with SketchUp and HTB2. In: *Solar Building Skins, Bressanone,*. Available at: http://orca.cf.ac.uk/41395/.

Bassett, T. and Waldron, D. 2013. Energy modelling in Wales: looking ahead to 2050. *Made at WSA 8* , pp. 40–41.

BBC News 2021. Suez Canal: Ever Given container ship shifted from shoreline. Available at: https://www.bbc.co.uk/news/world-middle-east-56559904. [Accessed: 30 March 2021].

Benis, K. et al. 2015. Building-Integrated Agriculture (BIA) In Urban Contexts : Testing A Simulation-Based Decision Support Workflow IN + Center for Innovation , Technology and Policy Research , IST , Lisbon , Portugal Building Technology , Massachusetts Institute of Technol.

Benis, K. et al. 2017a. Building-Integrated Agriculture (BIA) In Urban Contexts : Testing A Simulation-Based Decision Support Workflow. In: *15th International Building Performance Simulation Association (IBPSA) Conference, San Francisco, USA.*, pp. 1798–1807. doi: 10.26868/25222708.2017.479.

Benis, K. et al. 2017b. Development of a simulation-based decision support workflow for the implementation of Building-Integrated Agriculture (BIA) in urban contexts. *Journal of Cleaner Production* 147, pp. 589–602. doi: 10.1016/j.jclepro.2017.01.130.

Benis, K. et al. 2018. Urban foodprints (UF) - Establishing baseline scenarios for the sustainability assessment of high-yield urban agriculture. *International Journal of Design and Nature and Ecodynamics* 13(4), pp. 349–360. doi: 10.2495/DNE-V13-N4-349-360.

Benis, K. and Ferrão, P. 2018. Commercial farming within the urban built environment – Taking stock of an evolving field in northern countries. *Global Food Security* 17(November 2017), pp. 30–37.

Benke, K. and Tomkins, B. 2017. Future food-production systems: Vertical farming and controlled-environment agriculture. *Sustainability: Science, Practice, and Policy* 13(1), pp. 13–26.

Berto, R. 2005. Exposure to restorative environments helps restore attentional capacity. *Journal of Environmental Psychology* 25, pp. 249–259.

Besthorn, F.H. 2013. Vertical Farming: Social Work and Sustainable Urban Agriculture in an Age of Global Food Crises. *Australian Social Work* 66(2), pp. 187–203.

Bingham-Hall, P. 2016. *Garden City Mega City Rethinking Cities for the Age of Global Warming*. Pesaro Publishing.

Boesiger, W. and Stonorov, O. 1937. *Le Corbusier et Pierre Jeanneret. Oeuvre complete. Vol. 1: 1910-1929*. Éditions d Architecture.

Bojic, M. et al. 2002. Energy performance of windows in high-rise residential buildings in Hong Kong. *Energy and Buildings* 34(1), pp. 71–82. doi: 10.1016/S0378-7788(01)00079-2.

Booth, A. et al. 2012. *Systematic Approaches to a Successful Literature Review*. SAGE Publications.

Bourget, C.M. 2008. An introduction to LEDs. *Hortscience* 43

Breuste, J. et al. 2013a. Applied urban ecology for sustainable urban environment. *Urban Ecosystems* 16(4), pp. 675–680.

Breuste, J. et al. 2013b. Scaling down the ecosystem services at local level for urban parks of three megacities. *Hercynia N.F.* 46(October), pp. 1–20.

Brown, C. and Lundholm, J. 2015. Microclimate and substrate depth influence green roof plant community dynamics. *Landscape and Urban Planning* 143, pp. 134–142. Available at: http://dx.doi.org/10.1016/j.landurbplan.2015.07.009. [Accessed: 9 August 2018].

Broyles, T.D. 2008. Defining the architectural Typology of the Urban Farm. In: *PLEA 2008 - 25th Passive and Low Energy Architecture Conference*.

Bustami, R.A. et al. 2018. Vertical greenery systems: A systematic review of research trends. *Building and Environment* 146(September), pp. 226–237.

Butturini, M. and Marcelis, L. 2020. Vertical farming in Europe. In: Toyoki, K. et al. eds. *Plant Factory*. Elsevier Inc., pp. 77–91. doi: 10.1016/b978-0-12-816691-8.00004-2.

Cadillo-Benalcazar, J.J. et al. 2020. A multiscale integrated analysis of the factors characterizing the sustainability of food systems in Europe. *Journal of Environmental Management* 271(March).

Cattarin, G. et al. 2016. Outdoor test cells for building envelope experimental characterisation - A literature review. *Renewable and Sustainable Energy Reviews* 54, pp. 606–625.

Chen, W.T. et al. 2013. An automatic plant growth measurement system for plant factory. In: *IFAC Proceedings Volumes (IFAC-PapersOnline)*. IFAC, pp. 323–327. Available at: http://dx.doi.org/10.3182/20130327-3-JP-3017.00073. [Accessed: 9 October 2018].

Chen, W.T. et al. 2016. An automated and continuous plant weight measurement system for plant factory. *Frontiers in Plant Science* 7(MAR2016). doi: 10.3389/fpls.2016.00392.

Cheng, X. et al. 2015. Influence of Park Size and Its Surrounding Urban Landscape Patterns on the Park Cooling Effect. *Journal of Urban Planning and Development* 141(3), p. A4014002. Available at: http://ascelibrary.org/doi/10.1061/%28ASCE%29UP.1943-5444.0000256. [Accessed: 23 July 2019].

Citherlet, S. et al. 2001. Integration in building physics simulation. *Energy and Buildings* 33(5), pp. 451–461. doi: 10.1016/S0378-7788(00)00108-0.

Clark, V.L.P. and Creswell, J.W. 2008. *The Mixed Methods Reader*. SAGE Publications. Available at: https://books.google.co.uk/books?id=iBr6Y7cBmOQC. [Accessed: 14 June 2016].

ClemsonUniversity Institute of Applied Ecology 2011. *Charleston Vertical Farm Design Feasibility Study*.

Cohen, P.S. and Naginski, E. 2014. *The Return of Nature Sustaining Architecture in the face of Sustainability*. New York: Routledge.

Colnago, P. et al. 2021. Closing sustainability gaps on family farms: Combining on-farm co-innovation and model-based explorations.

Agricultural Systems 188(June 2020). doi: 10.1016/j.agsy.2020.103017.

Coma Bassas, E. et al. 2020. A review of the evolution of green residential architecture. *Renewable and Sustainable Energy Reviews* 125(June 2018), p. 109796. Available at: https://doi.org/10.1016/j.rser.2020.109796. [Accessed: 15 December 2020].

Couzens, V. 2012. Ken Yeang and Bioclimatic Architecture. Available at: https://www.architecture.org.au/news/enews/354-ken-yeang-and-bioclimatic-architecture [Accessed: 5 January 2019].

Creswell, J.W. 2014. *A Concise Introduction to Mixed Methods Research*. SAGE Publications. Available at: https://books.google.co.uk/books?id=51UXBAAAQBAJ. [Accessed: 14 June 2016].

Creswell, J.W., Plano Clark, V.L., Gutmann, M. L. and Hanson, W.E. 2003. Advanced Mixed-Methods Research Design. In: Tashakkori, A. and Teddlie, C. (Eds.), *Handbook of mixed methods in social and behavioral research* pp. 209–240. Thousand Oaks, CA: Sage.

Dash, S.P. 2018. Application of biomimicry in building design. *International Journal of Civil Engineering and Technology* 9(2), pp. 644–660.

Daudt, H. et al. 2013. Enhancing the Scoping Study Methodology: A Large, Interprofessional Team’s Experience with Arksey and O’Malley’s Framework. *BMC Medical Research Methodology* 13. doi: 10.1186/1471-2288-13-48.

Davis, M. and Hirmer, S. 2015. The potential for vertical gardens as evaporative coolers: An adaptation of the ‘Penman Monteith Equation’. *Building and Environment* 92, pp. 135–141. Available at: http://dx.doi.org/10.1016/j.buildenv.2015.03.033. [Accessed: 28 July 2017].

Despommier, D. 1999. *The Vertical Farm Feeding the World in the 21st Century*. 1st ed. Picador.

Despommier, D. 2009. The Rise of Vertical Farms. *Scientific American* , pp. 80–87.

Despommier, D. 2010. *The Vertical Farm*. USA: Picador.

Despommier, D. 2013. The Vertical Farm: A Keystone Concept for the the Ecocity - TED Talk x Warwick. Available at: https://www.youtube.com/watch?v=mwaZc7B8Hnc. [Accessed: 14 June 2016].

Despommier, D. 2014. Vertical Farms in Horticulture. In: *Encyclopedia of Food and Agricultural Ethics*. Kaplan PBT., pp. 1791–1799. Available at: http://link.springer.com/10.1007/978-94-007-0929-4_88. [Accessed: 20 August 2017].

DLR 2015. *Vertical Farm 2.0 - Designing and economically feasible vertical farm - a combined European endevour for sustainable urban agriculture*.

Doane, D.H. 1944. Vertical Farm Diversification. *Journal of Farm*

Economics Oxford 26(2), pp. 373–378.

El-Zeiny, R.M.A. 2012. Biomimicry as a Problem Solving Methodology in Interior Architecture. *Procedia - Social and Behavioral Sciences* 50(July), pp. 502–512.

Englund, O. et al. 2020. Beneficial land use change: Strategic expansion of new biomass plantations can reduce environmental impacts from EU agriculture. *Global Environmental Change* 60(December 2018), p. 101990. Available at: https://doi.org/10.1016/j.gloenvcha.2019.101990. [Accessed: 14 November 2020].

Enzi, V. et al. 2017. Nature-Based Solutions and Buildings - The Power of Surfaces to Help Cities Adapt to Climate Change and to Deliver Biodiversity. In: Kabisch, N. et al. eds. *Nature-Based Solutions to Climate Change Adaptation in Urban Areas. Theory and Practice of Urban Sustainability Transitions*. Cham: Springer, pp. 159–183. Available at: https://doi.org/10.1007/978-3-319-56091-5_10. [Accessed: 26 June 2018].

Fallmann, J. and Emeis, S. 2020. How to bring urban and global climate studies together with urban planning and architecture? *Developments in the Built Environment* 4(August), p. 100023. Available at: https://doi.org/10.1016/j.dibe.2020.100023. [Accessed: 15 January 2021].

FAO et al. 2017. The State of Food Security and Nutrition in the World 2017. Building resilience for peace and food security. Rome, FAO., pp. 1–54. doi: I4646E/1/05.15.

Farmbox Green 2019. Farmbox Green. Available at: https://www.farmboxgreens.com/. [Accessed: 13 December 2019].

Farquhar, D. 2020. Webinar: 'What technologies would help to grow trust for Vertical Farmers?'- 3rd Sep2020.

Finkelstein, N.D. et al. 2005. When learning about the real world is better done virtually: A study of substituting computer simulations for laboratory equipment. *Phys. Rev. ST Phys. Educ. Res.* 1(1), pp. 101031–101038. doi: 10.1103/PhysRevSTPER.1.010103.

Fischetti, M. 2008. Growing Vertical: Skyscraper Farming. *Scientific American* , pp. 74–79.

Franchini, L. 2016. *Vertical farm: perspective of development introduction : one concept for different realities*.

Frediani, K. 2011. Sustainable food production in the modern zoo and its wider role in a time of global change. In: Incoll, L. D. ed. *UK Controlled Environment Users' Group*.

Garcia-Holguera, M. et al. 2015. Ecosystem biomimetics for resource use optimization in buildings. *Building Research & Information* . doi: 10.1080/09613218.2015.1052315.

Garg, A. and Balodi, R. 2014. Recent Trends in Agriculture: Vertical Farming and Organic Farming. *Advances in Plants & Agriculture Research*

1(4)

Garg, S. 2017. *Impact of Overpopulation on Land Use Pattern*. doi: 10.4018/978-1-5225-1683-5.ch008.

Gillott, M. et al. 2010. Low-carbon housing design informed by research. *Proceedings of the Institution of Civil Engineers: Engineering Sustainability* 163(2), pp. 77–87. doi: 10.1680/ensu.2010.163.2.77.

Gillott, M. et al. 2014. *Vertical Farming and Urban Agriculture conference 2014*. UK. Available at: https://nottingham.mediaspace.kaltura.com/media/Vertical+Farming+and+Urban+Agriculture+conference+2014/1_9nzjjqkq. [Accessed: 28 October 2017].

Goodsell, W.D. 1951. Vertical Farm Diversification. *Journal of Farm Economics* 33(2), pp. 266–268. doi: 10.2307/1233599.

Gough, D. et al. 2012. *An Introduction to Systematic Reviews*. SAGE Publications.

Graamans, L. et al. 2017. Plant factories; crop transpiration and energy balance. *Agricultural Systems* 153, pp. 138–147. Available at: http://dx.doi.org/10.1016/j.agsy.2017.01.003. [Accessed: 29 November 2017].

Graamans, L. et al. 2018. Plant factories versus greenhouses: Comparison of resource use efficiency. *Agricultural Systems* 160(November 2017), pp. 31–43. doi: 10.1016/j.agsy.2017.11.003.

Graamans, L. et al. 2020. Plant factories: Reducing energy demand at high internal heat loads through façade design. *Applied Energy* 262, p. 114544. Available at: https://doi.org/10.1016/j.apenergy.2020.114544. [Accessed: 01 December 2020].

Graamans, L.J.A. 2015. *VERTICAL - The re-development of vacant urban structures into viable food production centres utilising agricultural production techniques*. Available at: https://repository.tudelft.nl/islandora/object/uuid:f9dd86ce-22a9-4dfe-b66e-ef55230e3856/?collection=research. [Accessed: 22 January 2018].

Gras, C. and Cáceres, D.M. 2020. Technology, nature's appropriation and capital accumulation in modern agriculture. *Current Opinion in Environmental Sustainability* 45, pp. 1–9. doi: 10.1016/j.cosust.2020.04.001.

Groat, L.N. and Wang, D. 2013. *Architectural Research Methods*. Wiley. Available at: https://books.google.co.uk/books?id=sUf5DPJyEqAC. [Accessed: 14 June 2016].

Growup Farm Website. Available at: hhttps://www.growupfarms.co.uk/OUR-HISTORY/ [Accessed: 16 March 2021]

Guimapang, K. 2019. In Jakarta residents living in a 'suburb in the sky'. Available at: https://archinect.com/news/article/150150240/in-jakarta-residents-are-living-in-a-suburb-in-the-sky [Accessed: 14 November

2019].

Gupta, M. and Ganapuram, S. 2019. *Vertical Farming Using Information and Communication*.

Hanks, C. 2009. *Technology and Values: Essential Readings*. Wiley. Available at: https://books.google.com.ag/books?id=BgYc9_ldWFYC. [Accessed: 21 November 2018].

Harkness, C. et al. 2021. Stability of farm income: The role of agricultural diversity and agri-environment scheme payments. *Agricultural Systems* 187(December 2020). doi: 10.1016/j.agsy.2020.103009.

Hassan, M.A. et al. 2011. Modeling and validation of the thermal performance of an affordable, energy efficient, healthy dwelling unit. *Building Simulation* 4(3), pp. 255–262. doi: 10.1007/s12273-011-0024-9.

Hennink, M. et al. 2010. *Qualitative Research Methods*. SAGE Publications. Available at: https://books.google.co.uk/books?id=rmJdyLc8YW4C. [Accessed: 30 May 2017].

Higgins, C. 2016. Current status of commercial vertical farms with LED lighting market in north america. In: Kozai, T. et al. eds. *LED Lighting for Urban Agriculture*. Springer, pp. 309–316.

Hirama, J. 2015. The History and Advanced Technology of Plant Factories. *Environment Control in Biology* 53(2), pp. 47–48.

Holland Hydroponics & Horticulture 2016. Hydroponics & Horticulture. Available at: http://www.hydroponics.co.uk/ [Accessed: 8 September 2016].

Howard, E. 1965. *Garden Cities of To-Morrow*. MIT Press.

Huang, J. et al. 2020. Urban Building Energy and Climate (UrBEC) simulation: Example application and field evaluation in Sai Ying Pun, Hong Kong. *Energy and Buildings* 207. doi: 10.1016/j.enbuild.2019.109580.

Hughes, S. 2018. *Vertical Farming: does the economic model work? - Nuffield Report*. Available at: https://www.nuffieldinternational.org/live/Report/UK/2017/sarah-hughes. [Accessed: 20 September 2019].

Huovila, P. et al. 2007. *Buildings and climate change: Status, challenges and opportunities*. doi: ISBN: 987-92-807-3064-7 DTI/1240/PA.

IFRC 2016. *World Disasters Report 2016. Resilience : saving lives today, investing for tomorrow*. doi: 10.1037/e569662006-003.

Ivankova, N.V., Creswell, J.W. and Stick, S.L. 2006. Using Mixed-Methods Sequential Explanatory Design: From Theory to Practice. *Field Methods* 18(1), pp. 3–20. Doi:10.1177/1525822X05282260

Jack, R. 2015. *Building Diagnostics: Practical Measurement of the Fabric Thermal Performance of Houses*. Loughborough University. Available at: http://www.innovationresearchfocus.org.uk/Issues/100/IRF100_BIS.html . [Accessed: 28 July 2019].

Jans-Singh, M. et al. 2019. Monitoring The Performance Of An Underground Hydroponic Farm. 2019, pp. 133–141. doi: 10.1680/icsic.64669.133.

Jick, T. 1979. Mixing Qualitative and Quantitative Methods : Triangulation in Action. *Administrative Science Quarterly* 24(4), pp. 602–611.

Johnson, M.P. 2001. Environmental impacts of urban sprawl: A survey of the literature and proposed research agenda. *Environment and Planning A* 33(4), pp. 717–735.

Jones, B. 2013. *Instructions for growing tomatoes*. Createspace.

Jones, P. et al. 2013. Intensive Building Energy Simulation at Early Design Stage. In: *IBPSA 2013*., pp. 862–869.

Jones, P. et al. 2017. Five energy retrofit houses in South Wales. *Energy and Buildings* 154, pp. 335–342. doi: 10.1016/j.enbuild.2017.08.032.

Kalantari, F. et al. 2017a. A Review of Vertical Farming Technology: A Guide for Implementation of Building Integrated Agriculture in Cities. *Advanced Engineering Forum* 24(October), pp. 76–91. doi: 10.4028/www.scientific.net/AEF.24.76. [Accessed: 8 May 2016].

Kalantari, F. et al. 2017b. Opportunities and Challenges in Sustainability of Vertical Farming: A Review. *Journal of Landscape Ecology* 2(2). doi: 10.12720/joaat.2.2.98-105.

Kalantari, F. et al. 2018. The Importance of the Public Acceptance Theory in Determining the Success of the Vertical Farming Projects. *Journal of Management Research Practice* 10(1)

Khalil, H.I. and Wahhab, K.A. 2020. Advantage of vertical farming over horizontal farming in achieving sustainable city, Baghdad city-commercial street case study. *IOP Conference Series: Materials Science and Engineering* 745(1). doi: 10.1088/1757-899X/745/1/012173.

Khan, R.R.A. and Ahmed, V. 2017. Building Information Modelling and Vertical Farming: Data integration to manage facilities and processes. *Facilities* 35(13/14), pp. 710–724.

Khandaker, M. and Kotzen, B. 2018. The potential for combining living wall and vertical farming systems with aquaponics with special emphasis on substrates. *Aquaculture Research* 49(4), pp. 1454–1468. doi: 10.1111/are.13601.

Khodakarami, J. et al. 2009. Reducing the demands of heating and cooling in Iranian hospitals. *Renewable Energy* 34(4), pp. 1162–1168. Available at: http://dx.doi.org/10.1016/j.renene.2008.06.023. [Accessed: 8 August 2017].

Kivimaa, P. et al. 2021. Moving beyond disruptive innovation: A review of disruption in sustainability transitions. *Environmental Innovation and Societal Transitions* 38(December 2020), pp. 110–126. Available at: https://doi.org/10.1016/j.eist.2020.12.001. [Accessed: 22 January 2021].

Koolhaas, R. 2004. *Delirio de Nueva York*. Editorial Gustavo Gili, S.L.

Kosorić, V. et al. 2019. Survey on the social acceptance of the productive façade concept integrating photovoltaic and farming systems in high-rise public housing blocks in Singapore. *Renewable and Sustainable Energy Reviews* 111(April), pp. 197–214. doi: 10.1016/j.rser.2019.04.056.

Koyama, T. et al. 2013. Identification of key plant traits contributing to the cooling effects ofgreen façades using freestanding walls. *Building and Environment* 66, pp. 96–103.

Kozai, T. 2013a. Plant factory in Japan - current situation and perspectives plant factory in Japan - current situation and perspectives. *Chronica Horticulturae* 53, pp. 8–11.

Kozai, T. 2013b. Resource use efficiency of closed plant production system with artificial light: concept, estimation and application to plant factory. *Proceedings of the Japan Academy. Series B, Physical and biological sciences* 89(10), pp. 447–61. Available at: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3881955&tool=pmcentrez&rendertype=abstract. [Accessed: 20 July 2017].

Kozai, T. 2014. Role of Plant Factory with Artificial Light (PFAL) in Urban Horticulture and Next Generation Lifestyle.

Kozai, T. et al. 2016a. *LED Lighting for Urban Agriculture*. Springer Singapore.

Kozai, T. et al. 2016b. *Plant Factory An Indoor Vertical Farming System for Efficient Quality Food Production*. Academic Press, Elsevier.

Kozai, T. 2018. *Smart Plant Factory: The Next Generation Indoor Vertical Farms*. Springer Singapore. Available at: https://books.google.co.uk/books?id=i2J5DwAAQBAJ. [Accessed: 31 July 2019].

Kuru, A. et al. 2019. Biomimetic adaptive building skins: Energy and environmental regulation in buildings. *Energy and Buildings* 205, p. 109544. Available at: https://doi.org/10.1016/j.enbuild.2019.109544. [Accessed: 6 July 2020].

Lewis-Jones, K.E. 2016. People and Plants - World-Making with Plants. *Environment and Society: Advances in Research* 7(1), pp. 1–7. doi: 10.3167/ares.2016.070101.

Lewis, P. and Alexander, D. 1990. HTB2: A Flexible Model for Dynamic Building Simulation. *Building and Environment* 25(1), pp. 7–16.

Li, J. et al. 2011. Impacts of landscape structure on surface urban heat islands: A case study of Shanghai, China. *Remote Sensing of Environment* 115(12), pp. 3249–3263.

Li, K. et al. 2016. Improving Light Distribution by Zoom Lens for Electricity Savings in a Plant Factory with Light-Emitting Diodes. *Frontiers in Plant Science* 7(February), pp. 1–11. Available at: http://journal.frontiersin.org/Article/10.3389/fpls.2016.00092/abstract. [Accessed: 29 November 2017].

Liebe, D.L. et al. 2020. Contributions of dairy products to environmental impacts and nutritional supplies from United States agriculture. *Journal of Dairy Science* 103(11), pp. 10867–10881. Available at: http://dx.doi.org/10.3168/jds.2020-18570. [Accessed: 5 December 2020].

Lim, C. and Liu, E. 2010. *Smartcities + eco-warriors*. Routledge.

Lim, C.J. and Liu, E. 2019. *Smartcities, Resilient Landscapes and Eco-Warriors*. Taylor & Francis. Available at: https://books.google.co.uk/books?id=VYmUDwAAQBAJ. [Accessed: 5 December 2020].

Liu, S. and Teng, P. 2017. High-Tech Plant Factories: Challenges and Way Forward.

Lomas, K.J. 1996. The U.K. Applicability Study: An Evaluation of Thermal Simulation Programs for Passive Solar House Design. *Building and Environment* 31(3), pp. 197–206. doi: 10.1016/0360-1323(95)00050-X.

Lu, M. and Qu, Y. 2018. Biodiversity conservation development based on Systematic Conservation Planning in urban areas. *Energy Procedia* 153, pp. 484–488. doi: 10.1016/j.egypro.2018.10.027.

Luna-Maldonado, A.I. et al. 2016. Editorial: Advances and Trends in Development of Plant Factories. *Frontiers in Plant Science* 7(December), pp. 1–3. Available at: http://journal.frontiersin.org/article/10.3389/fpls.2016.01848/full. [Accessed: 8 December 2017].

Lurie-Luke, E. 2014. Product and technology innovation: what can biomimicry inspire? *Biotechnology advances* 32(8), pp. 1494–505.

Malott, K. et al. 2015. Immeuble Villas LeCobusier:1922. Available at: https://www.tboake.com/2015/125ResidentialPDF/Immeuble Villas.pdf. [Accessed: 25 September 2019].

Marston, J. 2019. What Plantagon's Bankruptcy Could Tell Us About the Future of Large-Scale Vertical Farming. Available at: https://www.igrow.news/igrownews/what-plantagons-bankruptcy-could-tell-us-about-the-future-of-large-scale-vertical-farming [Accessed: 10 October 2019].

Martin, M. and Molin, E. 2019. Environmental assessment of an urban vertical hydroponic farming system in Sweden. *Sustainability (Switzerland)* 11(15), pp. 1–14. doi: 10.3390/su11154124.

Martínez Muñoz, A. 2020. Humanizing the Vertical City: Three Strategies To Bring the Ground Level Closer To the Clouds. *The Sustainable City XIV* 1(December 2020), pp. 57–69. doi: 10.2495/sc200061.

Mavrigiannaki, A. and Ampatzi, E. 2016. Latent heat storage in building elements: A systematic review on properties and contextual performance factors. *Renewable and Sustainable Energy Reviews* 60, pp. 852–866. Available at: http://dx.doi.org/10.1016/j.rser.2016.01.115. [Accessed: 24 January 2017].

Mitchell, C.A. and Sheibani, F. 2015. LED advancements for plant-factory artificial lighting (Chapter 10). In: Kozai, T. et al. eds. *Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production*. 1st ed. Academic Press, pp. 167–184. doi: 10.1016/B978-0-12-816691-8.00010-8.

Moher, D. et al. 2010. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *International Journal of Surgery* 8(5), pp. 336–341. doi: 10.1016/j.ijsu.2010.02.007.

Molin, E. and Martin, M. 2018a. *Assessing the energy and environmental performance of vertical farming hydroponic farming*.

Molin, E. and Martin, M. 2018b. *Reviewing the energy and environmental performance of vertical farming systems*.

MoMA 2002. SITE, James Wines highrise of homes, project exterior perspective. Available at: https://www.moma.org/collection/works/709 [Accessed: 11 March 2020]. [Accessed: 17 August 2020].

MoMA 2018. LeCobusier - Vertical Garden City. Available at: https://www.moma.org/collection/works/961. [Accessed: 5 December 2020].

Van Mourik, S. et al. 2021. Introductory overview: Systems and control methods for operational management support in agricultural production systems. *Environmental Modelling & Software* 139, p. 105031. Available at: https://doi.org/10.1016/j.envsoft.2021.105031. [Accessed: 1 March 2021].

Nagore Setién, I. 2011. Towards an open and user driven housing architecture: Layers principle, infrastructure types and technical devices. (2010), pp. 96–101.

Newbean Capital and Singapore Farming 2016. *The Rise of Asia's Indoor Agriculture Industry*.

Nicholson, C.F. et al. 2021. Food security outcomes in agricultural systems models: Current status and recommended improvements. *Agricultural Systems* 188(December 2020), p. 103028. Available at: https://doi.org/10.1016/j.agsy.2020.103028. [Accessed: 1 February 2021].

NRN-LCEE 2018. Plants & Architecture. Available at: http://nrn-lcee.ac.uk/plants-architecture/index.php.en [Accessed: 20 August 2018].

Oldewurtel, F. et al. 2012. Use of model predictive control and weather forecasts for energy efficient building climate control. *Energy and Buildings* 45, pp. 15–27. Available at: http://dx.doi.org/10.1016/j.enbuild.2011.09.022. [Accessed: 22 May 2017].

Orsini, F. et al. 2013. Urban agriculture in the developing world: A review. *Agronomy for Sustainable Development* 33(4), pp. 695–720. doi: 10.1007/s13593-013-0143-z.

Parra, D. et al. 2014. Modeling of PV generation, battery and hydrogen storage to investigate the benefits of energy storage for single dwelling. *Sustainable Cities and Society* 10(March 2012), pp. 1–10. Available at: http://dx.doi.org/10.1016/j.scs.2013.04.006. [Accessed: 19 April 2021].

Pawlyn, M. 2011. *Biomimicry in Architecture*. London: RIBA Publishing.

Pérez, G. et al. 2014. Vertical Greenery Systems (VGS) for energy saving in buildings: A review. *Renewable and Sustainable Energy Reviews* 39, pp. 139–165.

pH Hydro 2014. Powerhouse Hydroponics. Available at: http://www.powerhousehydroponics.com/aeroponics-101-facts-about-soilless-growing-technology/ [Accessed: 8 September 2016].

Philips 2019. Philips Research Eindhoven. Available at: https://www.philips.com/a-w/research/locations/eindhoven.html [Accessed: 11 September 2019].

Piccolino, J. 2013. Memo 2: A Timeline of Vertical Farming. Available at: https://eportfolios.macaulay.cuny.edu/macbride13/research/timelines/memo-2-a-timeline-of-vertical-farming/ [Accessed: 5 August 2017].

Plan 2B Green 2011. Vertical Farming. Available at: http://www3.jjc.edu/ftp/wdc12/jjurkiewicz/history.html. [Accessed: 1 March 2016].

PlantLab 2018. PlantLab website. Available at: https://www.plantlab.com/ [Accessed: 12 December 2018].

Prakash, G. 2018. Review of the food processing supply chain literature: a UK, India bilateral context. *Journal of Advances in Management Research* 15(4), pp. 457–479. doi: 10.1108/JAMR-12-2017-0116.

Proksch, G. et al. 2019. Aquaponics in the Built Environment. In: Goddek, S. et al. eds. *Aquaponics Food Production Systems*. Sprimger, Cham, pp. 523–558. doi: 10.1007/978-3-030-15943-6_21.

Rao, R. 2014. Biomimicry in Architecture. *International Journal of Advanced Research in Civil,Structural,Environmental and Infrastructure Engineering and Developing* , pp. 101–107.

RBG Kew 2016. *The State of the World’s Plants Report*. London.

Rhinoceros TM 2020. Rhinoceros Purchasing webpage. Available at: https://www.rhino3d.com/sales/europe/United_Kingdom/all/ [Accessed: 30 August 2020].

Rival, L. 2016. Botanical Ontologies Special Sect ion of the Journal of Ethnobiology Post-Face. *Journal of Ethnobiology* 36(1), pp. 147–149.

RockstrÖm, J. 2009. Planetary boundaries: exploring the safe operating space for humanity. *Ecology and Society* 14(2), p. 32.

Rosenzweig, C. et al. 2008. Attributing physical and biological impacts to anthropogenic climate change. *Nature* 453(7193), pp. 353–357. doi: 10.1038/nature06937.

Roser, M. and Ortiz-Ospina, E. 2018. World Population Growth. Available at: https://ourworldindata.org/world-population-growth [Accessed: 17 August 2018].

Ryymin, E. et al. 2020. How to digitally enhance bioeconomy collaboration:multidisciplinary research teamideation for technology innovation. *Technology Innovation Management Review* 10(11), pp. 31–39. doi: 10.22215/TIMREVIEW/1401.

Safikhani, T. et al. 2014. A review of energy characteristic of vertical greenery systems. *Renewable and Sustainable Energy Reviews* 40, pp. 450–462.

Samangooei, M. et al. 2016. Soil-less systems vs. soil-based systems for cultivating edible plants on buildings in relation to the contribution towards sustainable cities. *Future of Food: Journal on Food, Agriculture and Society* 4(2), pp. 24–39.

Sarkar, A. and Majumder, M. 2015. Opportunities and Challenges in sustainability of Vertical Eco-Farming: A Review. *Journal of Advanced Agricultural Technologies* 2(2), pp. 98–105.

Seguí, A.E. et al. 2017. From leisure to necessity: Urban allotments in Alicante province, Spain in times of crisis. *ACME* 16(2), pp. 276–304. Available at: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85026525566&partnerID=40&md5=65fe5e36bae29321b71a82a970d95042. [Accessed: 19 March 2018].

Shahidan, M.F. et al. 2012. An evaluation of outdoor and building environment cooling achieved through combination modification of trees with ground materials. *Building and Environment* 58, pp. 245–257. Available at: http://dx.doi.org/10.1016/j.buildenv.2012.07.012. [Accessed: 11 February 2016].

Shamshiri, R.R. et al. 2018. Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture. *International Journal of Agricultural and Biological Engineering* 11(1), pp. 1–22. doi: 10.25165/j.ijabe.20181101.3210.

Shao, Y. et al. 2016. Developing an economic estimation system for vertical farms. *International Journal of Agricultural and Environmental Information Systems* 7(2), pp. 26–51. doi: 10.4018/IJAEIS.2016040102.

Shao, Y. et al. 2021. The effects of vertical farming on indoor carbon dioxide concentration and fresh air energy consumption in office buildings. *Building and Environment* 195

Sharifi, A. 2016. From Garden City to Eco-urbanism: The quest for sustainable neighborhood development. *Sustainable Cities and Society* 20, pp. 1–16. Available at: http://dx.doi.org/10.1016/j.scs.2015.09.002. [Accessed: 19 May 2018].

Sheridan, M. 2016. Boundary Plants, the Social Production of Space, and Vegetative Agency in Agrarian Societies. *Environment and Society: Advances in Research* 7(1), pp. 29–49.

Silva, C.M. et al. 2015. Green roofs in Mediterranean areas – Survey and maintenance planning. *Building and Environment* 94, pp. 131–143.

Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360132315300780. [Accessed: 21 July 2019].

SITE 2015. Highrie of Homes, Theoretical project by SITE -1981. Available at: https://www.siteenvirodesign.com/content/high-rise-homes [Accessed: 5 December 2019].

SkyGreens 2014. About SkyGreen. Available at: https://www.skygreens.com/about-skygreens/ [Accessed: 5 July 2019].

Smith, P. et al. 2011. Making the Case for Plant Diversity. *Seed Science Research* 21(1), pp. 1–4.

Soderlund, J. and Newman, P. 2015. Biophilic architecture: a review of the rationale and outcomes. *AIMS Environmental Science* 2(4), pp. 950–969. doi: 10.3934/environsci.2015.4.950.

Solcerova, A. et al. 2017. Do green roofs cool the air? *Building and Environment* 111, pp. 249–255. Available at: http://dx.doi.org/10.1016/j.buildenv.2016.10.021. [Accessed: 14 October 2018].

Solemma 2020. DIVA- Design Iterate Validate Adapt. Available at: https://www.solemma.com/Diva.html [Accessed: 30 August 2020].

Somerville, C. et al. 2014. *Small-Scale Aquaponic Food Production: Integrated Fish and Plant Farming*. Rome.

Song, M.J. et al. 2014. Air anions enhance lettuce growth in plant factories. *Horticulture Environment and Biotechnology* 55(4), pp. 293–298. doi: 10.1007/s13580-014-1016-3.

Storey, N. et al. 2020. Webinar: 'The Road Ahead for Vertical Farming: Building Tomorrow's Industry Blueprint Today'.

Sun, T. et al. 2014. To irrigate or not to irrigate: Analysis of green roof performance via a vertically-resolved hygrothermal model. *Building and Environment* 73, pp. 127–137. Available at: http://dx.doi.org/10.1016/j.buildenv.2013.12.004. [Accessed: 19 August 2018].

Susorova, I. and Bahrami, P. 2013. Facade-integrated vegetation as an environmental sustainable solution for energy-efficient buildings. *Made at WSA 8* , pp. 69–77.

Tablada, A. et al. 2020. Architectural quality of the productive façades integrating photovoltaic and vertical farming systems: Survey among experts in Singapore. *Frontiers of Architectural Research* 9(2), pp. 301–318. doi: 10.1016/j.foar.2019.12.005.

Tenwolde, A. and Pilon, C.L. 2007. The Effect of Indoor Humidity on Water Vapor Release in Homes. *Thermal Performance of Exterior Envelopes of Whole Buildings X International Conference. ASHRAE* , pp. 1–9.

The Aquaponic Source 2016. What is aquaponics. Available at: https://www.theaquaponicsource.com/what-is-aquaponics/ [Accessed: 8

September 2016].

Thomaier, S. et al. 2014. Farming in and on urban buildings: Present practice and specific novelties of zero-acreage farming (ZFarming). *Renewable Agriculture and Food Systems* 30(1), pp. 43–54. doi: 10.1017/S1742170514000143.

Thuring, C.E. and Dunnett, N. 2014. Vegetation composition of old extensive green roofs (from 1980s Germany). *Ecological Processes* 3(1), p. 4. Available at: Ecological Processes.

Torcellini, P. et al. 2015. A pathway for net-zero energy buildings: Creating a case for zero cost increase. *Building Research and Information* 43(1), pp. 25–33. doi: 10.1080/09613218.2014.960783.

Torreggiani, D. et al. 2012. The urban nature of agriculture: Bidirectional trends between city and countryside. *Cities* 29(6), pp. 412–416. Available at: http://dx.doi.org/10.1016/j.cities.2011.12.006. [Accessed: 1 March 2021].

Tsitsimpelis, I. et al. 2016. Development of a grow-cell test facility for research into sustainable controlled-environment agriculture. *Biosystems Engineering* 150, pp. 40–53. doi: 10.1016/j.biosystemseng.2016.07.008.

Tsitsimpelis, I. and Taylor, C.J. 2014. *Micro – Climate Control in a Grow – Cell : System Development and Overview*. IFAC. doi: 10.3182/20140824-6-ZA-1003.01323.

Vanthoor, B.H.E. et al. 2011a. A methodology for model-based greenhouse design: Part 1, a greenhouse climate model for a broad range of designs and climates. *Biosystems Engineering* 110(4), pp. 363–377. doi: 10.1016/j.biosystemseng.2011.06.001.

Vanthoor, B.H.E. et al. 2011b. A methodology for model-based greenhouse design: Part 2, description and validation of a tomato yield model. *Biosystems Engineering* 110(4), pp. 378–395. doi: 10.1016/j.biosystemseng.2011.08.005.

Viljoen, A. et al. 2005. *Continuous Productive Uban Landscape (CPULs)*.

Viljoen, A. and Bohn, K. 2005. CPULs, Chapter 24. In: *Continuous Productive Urban Landscape (CPULs).*, pp. 239–250.

Viljoen, A. and Katrin Bohn 2014. *Second Nature Urban Agriculture Designing Productive Cities*. New York: Routledge.

Vucetich, J. et al. 2015. Evaluating whether nature's intrinsic value is an axiom of or anathema to conservation. *Conservation Biology* 29(2), pp. 1–12.

Waldron, D. et al. 2013. Embodied energy and operational energy: Case studies comparing different urban layouts. *Proceedings of BS 2013: 13th Conference of the International Building Performance Simulation Association* , pp. 1264–1271.

Waldron, D. 2017. Vertical Farms: Historic Development, Current State and Future Directions. In: Brotas, L. et al. eds. *PLEA 2017 Proceedings -*

Design To Thrive, Vol.1. Edinburgh, pp. 168–175.

Waldron, D. 2018. Evolution of Vertical Farms and the Development of a Simulation Methodology. *WIT Transactions on Ecology and the Environment* 217, pp. 975–986.

Wandersee, J.H. and Schussler, E. 2001. Toward a Theory of Plant Blindness. *Plant Science Bulletin* 47(1), pp. 2–8.

Wang, J. et al. 2016. Performance of introducing outdoor cold air for cooling a plant production system with artificial light. *Frontiers in Plant Science* 7(MAR2016), pp. 1–10. doi: 10.3389/fpls.2016.00270.

Ward R et al. 2018. Quantifying the Environmental and Energy Benefits of Food Growth in the Urban Environment. In: Kozai, T. ed. *Smart Plant Factory*. Singapore: Springer Singapore, pp. 245–287.

Welsh School of Architecture 2014. VirVil SketchUp Extension. Available at: http://u001.arch.cf.ac.uk/plugin/index.html [Accessed: 31 August 2018].

Wilmoth, J.-U.N. 2018. Press briefing upon release of data from World Urbanization Prospects: The 2018 Revision., pp. 1–4.

Wilson, J. and Sharples, S. 2015. *Evaluation of human work*. 4th editio. CRC Press.

Wohl, K., and James, W.O. 1942. The Energy Changes Associated with Plant Respiration. *The New Phytologist* 41(4) pp. 230–56. Available at: http://www.jstor.org/stable/2428730. [Accessed: 15 February 2019]

Wolch, J.R. et al. 2014. Urban green space, public health, and environmental justice: The challenge of making cities 'just green enough'. *Landscape and urban planning.* 125, pp. 234–244.

Xing, Q. et al. 2019. Experimental investigation on the thermal performance of a vertical greening system with green roof in wet and cold climates during winter. *Energy and Buildings* 183(November 2018), pp. 105–117. doi: 10.1016/j.enbuild.2018.10.038.

Yang, Q. 2014. *Prophase exploration on technologies of vertical farming and urban agriculture in China*.

Yik, F. et al. 2002. The influence of envelope characteristics to the energy behaviour of high-rise residential buildings. *Advances in Building Technology* 2, pp. 1289–1296. doi: 10.1016/b978-008044100-9/50160-1.

Zero Carbon Hub 2014. Closing the gap between Design & As Built Performance Evidence Review Report. *Zero Carbon Hub* (March), p. 80. Available at: www.zerocarbonhub.org. [Accessed: 26 September 2020].

Zimmerman-Loessl, C. et al. 2020. RICS Webinar: Food security in a warming world. Available at: https://www.rics.org/uk/wbef/megatrends/natural-environment/food-security-in-a-warming-world-key-points-from-our-recent-webinar/. [Accessed: 6 June 2020].

Zoetmulder, A. 2014. *Jean Renaudie: to give voice to that which was silent*. TU Delf.

Zune, M. et al. 2020. Vernacular passive design in Myanmar housing for thermal comfort. *Sustainable Cities and Society* 54(April 2019), p. 101992. Available at: https://doi.org/10.1016/j.scs.2019.101992. [Accessed: 23 January 2021].

Appendix 1

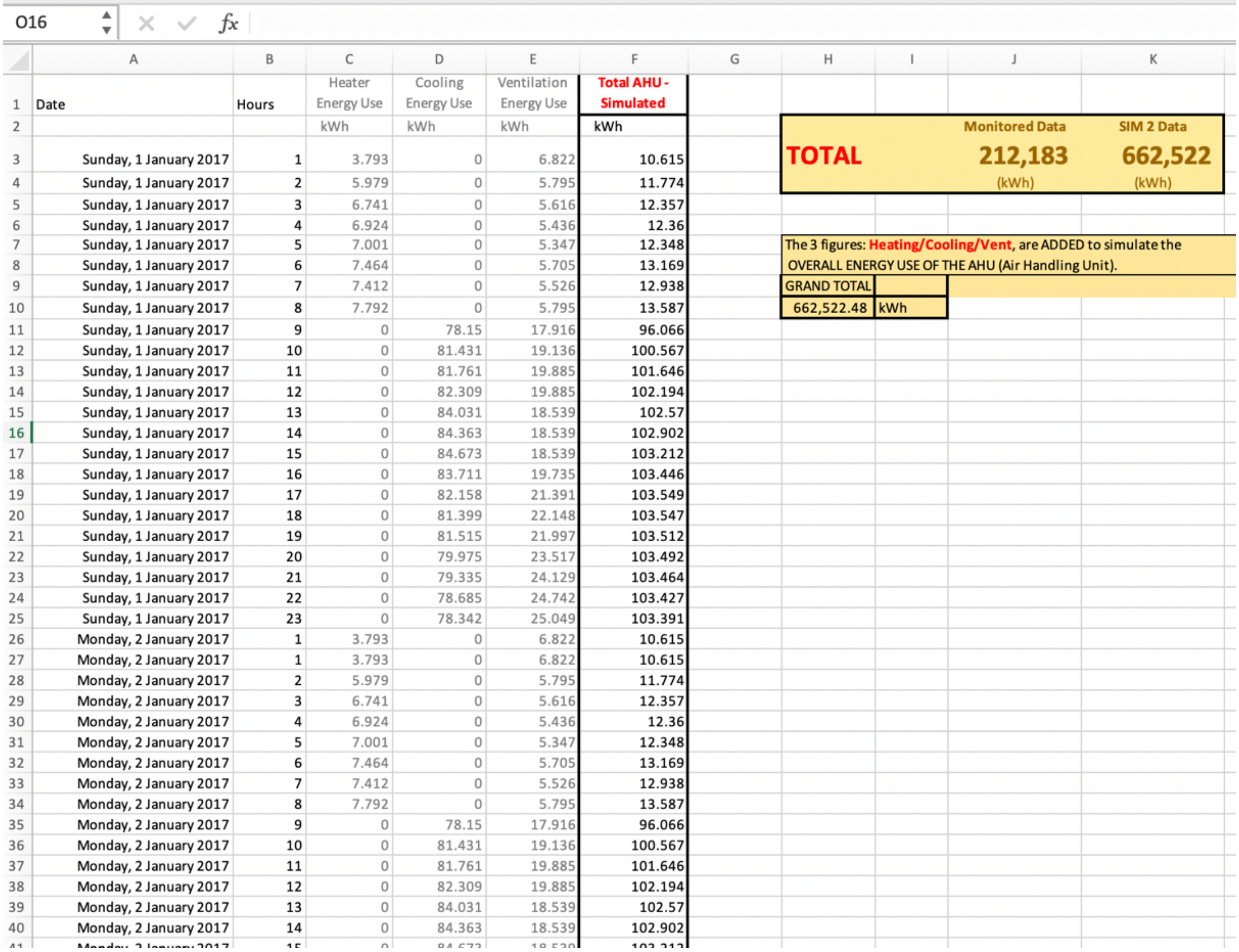
Stakeholder Engagement

	Contacted DATE	Response (YES/NO)	TOPIC
ACADEMIC CONTACTS			
Dr Li (East China Normal University - Shanghai) * The purpose of this contact was to engage with academic partners in a collaborative partner to submit a research porposal to undertake a	01/11/2015	YES	Student Mobility
AS A RESULT: Grant funding application for fieldwork in China (Newton Fund)- **Successful**	01/06/2016	YES	Student Mobility
Dickson Despommier - Columbia University, USA Prominet academic in the area of VF, therefore his advice and feedback can be valuable to my research	18/02/2016 22/02/2016	YES	General information and possibility to interview the "father of modern vertical farms"
Dr Ana Moragues, Cardiff University	08/02/2017	YES	Aiming to create links within our university with experience on VF
Dr Tim Patterson, South Wales University *	02/08/2017 22/08/2017	YES	To discuss options regarding setting up a VF case study coupled with Anaerobic digestion. Requested advice on location for my VF (attempt 2)
Dr Sandra Esteves, South Wales University	02/08/2017	YES	As above
Luuk Graamans, TU Delft University	13/02/2018	YES	To discuss his simulation choices and results
Mr Reinhart, MIT	25/04/2018	NO	As above
Paulo Ferrao, FCT, Portugal	26/04/2018	YES	As above
INDUSTRIAL CONTACTS			
Lu Xingmeng (VF in China)	20/05/2016	NO	Contacted him to arrange a visit to their VF in China
Prof Qichang Yang (VF in China)	20/05/2016	NO	Contacted him to arrange a visit to their VF in China
Neil Tapper (Cenin)*	03/11/2016	YES	Contacted him to discuss potential location for my VF case study (attempt 1)
Tom Webster (GrowUp VF in London)*	09/05/2017	YES	A number of meetings were held, one of them included a tour to their vertical farm
Jessica Brown (Modular Farms)	23/08/2017	YES	To discuss VF equipment and figures from the industry
Sophie Durnam (Salad Garden in Cardiff)	10/04/2018	YES	Contact at Bute Park Centre. Where I was hoping to develop a VF project. Sophie is part of Salad Gardens enterprise, based here. Discussed potential location for my VF case study (attempt 3)
Bill Walton (MaxiGrow, UK)	10/05/2018	YES	Looking for a quote for VF equipment (attempt 4)
Nico Hill (MaxiGrow, UK)	10/05/2018	YES	Looking for a quote for VF equipment (attempt 4)
Peter (Erith Horticulture Ltd, UK)	10/05/2018	YES	Looking for a quote for VF equipment (attempt 4)
Stephen Fry (V-Farms, HydroGarden)* Largest UK providors of VF equipment	10/05/2018	YES	Visit their VF facilities. Looking for a quote for VF equipment. (attempt 4)
BOTH:ACADEMIC/INDUSTRIAL CONTACTS			
Kevin Fredianni	23/03/2016	YES	Contacted him for a potential visit to his vertical farm. Paigton Zoo was the 1st recorded vertical farm built in the UK.
Andrew Blume (Associate of Vertical Farming, AVF)	23/08/2017	YES	Creating internation Links with the VF community
Mark Horler (Associate of Vertical Farming, AVF)	24/08/2017	YES	As above

Appendix 2
Information on Simulation Raw Data

That background data of the simulations undertaken on this study have not been included in these appendices, due to the sheer volume of this data. The simulated scenarios contained data for every hour, for every day of a full year (from 2016 – 2017). This volume of data was multiplied every time by the number of parameters investigated: relative humidity, internal and external temperature, etc. On top of this each scenario dad a series of tested variations. To include all the relevant raw data would easily take more than a thousand extra pages attached to these appendices. The relevant aspects of the raw data have been summarised in the several figures, tables and graphs provided on the main body of this thesis, but if the reader of this thesis have further queries related to the raw data, please feel free to get in touch with the author via email, Twitter or LinkedIn.

For instance, below a screenshot can be seen, of one of the excel files where the raw data has been organised and put together in Excel, in this instance, to make a direct comparison of the data obtained by simulation vs the monitored data of the physical vertical farm. This is hourly data for a full year and it's the comparison to achieve values related to the energy consumption of heating, colling and ventilation of the vertical farm. This is only a fraction of the raw data of the simulation undertaken for this study. To provide a scale of the size of the overall amount of data manged for this investigation. This comparison alone when transferred into word document its length is more than 250 pages.



O16

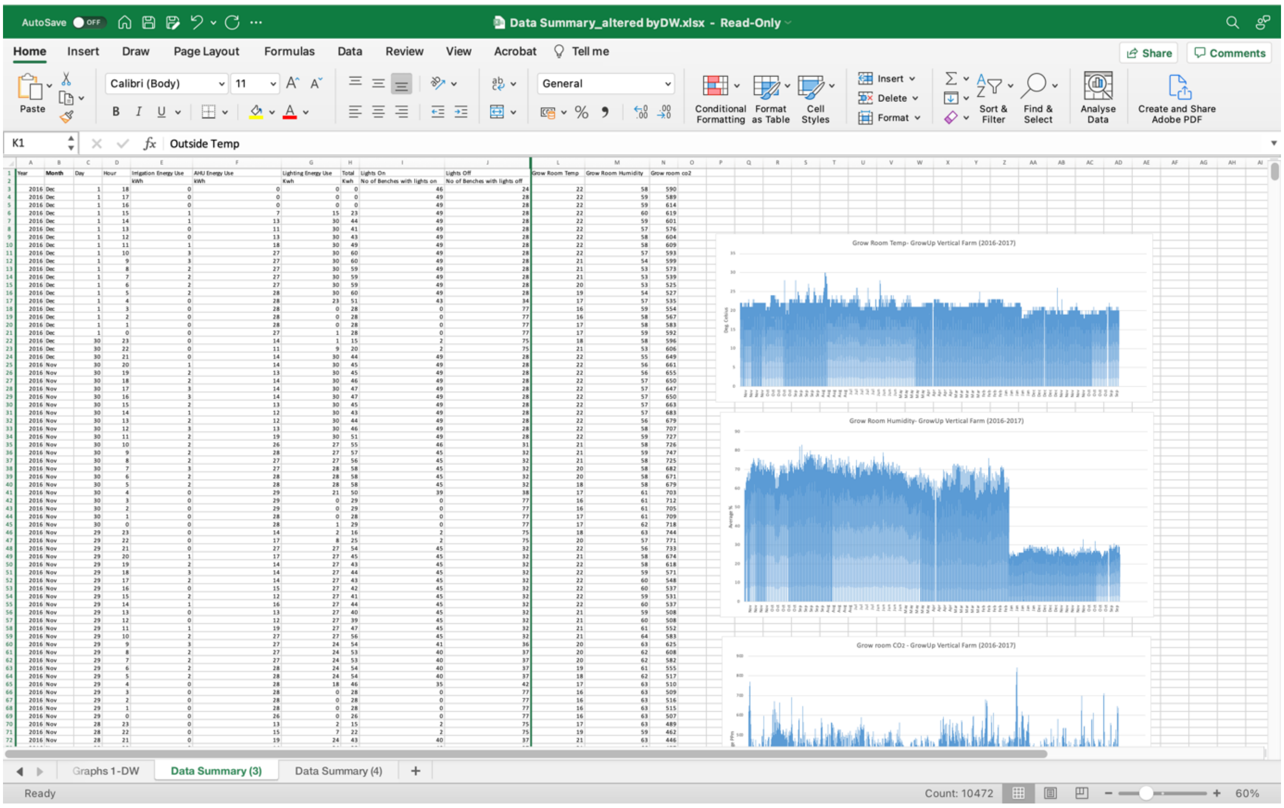
	A	B	C	D	E	F
1	Date	Hours	Heater Energy Use	Cooling Energy Use	Ventilation Energy Use	Total AHU - Simulated
2			kWh	kWh	kWh	kWh
3	Sunday, 1 January 2017	1	3.793	0	6.822	10.615
4	Sunday, 1 January 2017	2	5.979	0	5.795	11.774
5	Sunday, 1 January 2017	3	6.741	0	5.616	12.357
6	Sunday, 1 January 2017	4	6.924	0	5.436	12.36
7	Sunday, 1 January 2017	5	7.001	0	5.347	12.348
8	Sunday, 1 January 2017	6	7.464	0	5.705	13.169
9	Sunday, 1 January 2017	7	7.412	0	5.526	12.938
10	Sunday, 1 January 2017	8	7.792	0	5.795	13.587
11	Sunday, 1 January 2017	9	0	78.15	17.916	96.066
12	Sunday, 1 January 2017	10	0	81.431	19.136	100.567
13	Sunday, 1 January 2017	11	0	81.761	19.885	101.646
14	Sunday, 1 January 2017	12	0	82.309	19.885	102.194
15	Sunday, 1 January 2017	13	0	84.031	18.539	102.57
16	Sunday, 1 January 2017	14	0	84.363	18.539	102.902
17	Sunday, 1 January 2017	15	0	84.673	18.539	103.212
18	Sunday, 1 January 2017	16	0	83.711	19.735	103.446
19	Sunday, 1 January 2017	17	0	82.158	21.391	103.549
20	Sunday, 1 January 2017	18	0	81.399	22.148	103.547
21	Sunday, 1 January 2017	19	0	81.515	21.997	103.512
22	Sunday, 1 January 2017	20	0	79.975	23.517	103.492
23	Sunday, 1 January 2017	21	0	79.335	24.129	103.464
24	Sunday, 1 January 2017	22	0	78.685	24.742	103.427
25	Sunday, 1 January 2017	23	0	78.342	25.049	103.391
26	Monday, 2 January 2017	1	3.793	0	6.822	10.615
27	Monday, 2 January 2017	1	3.793	0	6.822	10.615
28	Monday, 2 January 2017	2	5.979	0	5.795	11.774
29	Monday, 2 January 2017	3	6.741	0	5.616	12.357
30	Monday, 2 January 2017	4	6.924	0	5.436	12.36
31	Monday, 2 January 2017	5	7.001	0	5.347	12.348
32	Monday, 2 January 2017	6	7.464	0	5.705	13.169
33	Monday, 2 January 2017	7	7.412	0	5.526	12.938
34	Monday, 2 January 2017	8	7.792	0	5.795	13.587
35	Monday, 2 January 2017	9	0	78.15	17.916	96.066
36	Monday, 2 January 2017	10	0	81.431	19.136	100.567
37	Monday, 2 January 2017	11	0	81.761	19.885	101.646
38	Monday, 2 January 2017	12	0	82.309	19.885	102.194
39	Monday, 2 January 2017	13	0	84.031	18.539	102.57
40	Monday, 2 January 2017	14	0	84.363	18.539	102.902

	Monitored Data	SIM 2 Data
TOTAL	212,183 (kWh)	662,522 (kWh)

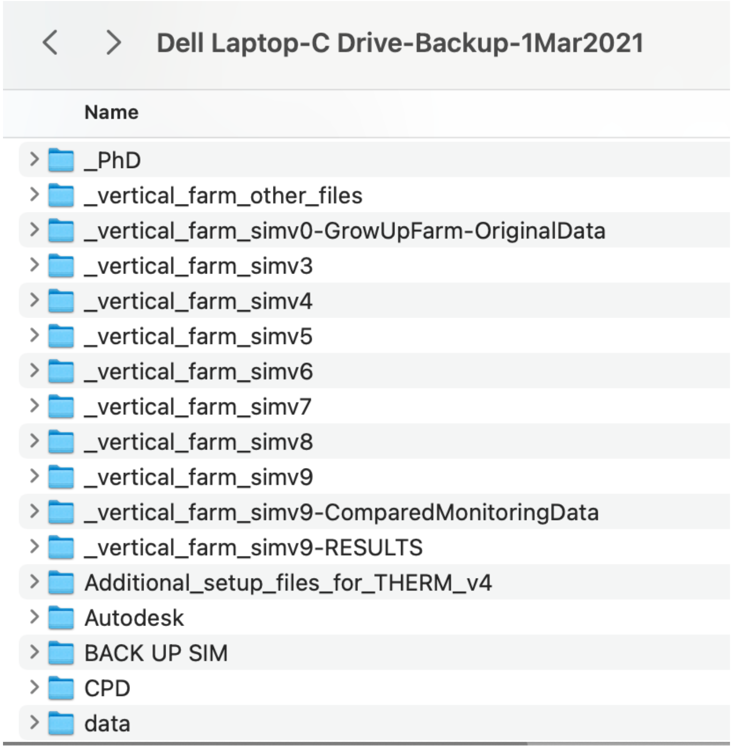
The 3 figures: **Heating/Cooling/Vent**, are ADDED to simulate the OVERALL ENERGY USE OF THE AHU (Air Handling Unit).

GRAND TOTAL	
662,522.48	kWh

Furthermore, besides the data pre- and post-simulation (i.e. input and output) another instance of the kind of processes that have been part of this analysis is to query and check for the quality of monitored data, before it can be compared to the simulation. When dealing with monitored data, the sets of information need to be "clean", to removing any potential value that can skew the data. The table below is a screen shot of the data received from GrowUp Vertical Farm being scrutinised and analysed to identify any odd data that might need to be "tidy up". The size of this data file will be of a similar size as the previously discussed (over 250 pages long).



Furthermore, the image to the right, is the list of the various simulation cycles that took place for this PhD investigation. Some of these folders have subfolder of further simulation with added variations, all of them with raw input and output data. The development of this simulation framework was an iterative process, where data from literature was gathered to inform the process, but also trial and error tests took place to


Dell Laptop-C Drive-Backup-1Mar2021

Name

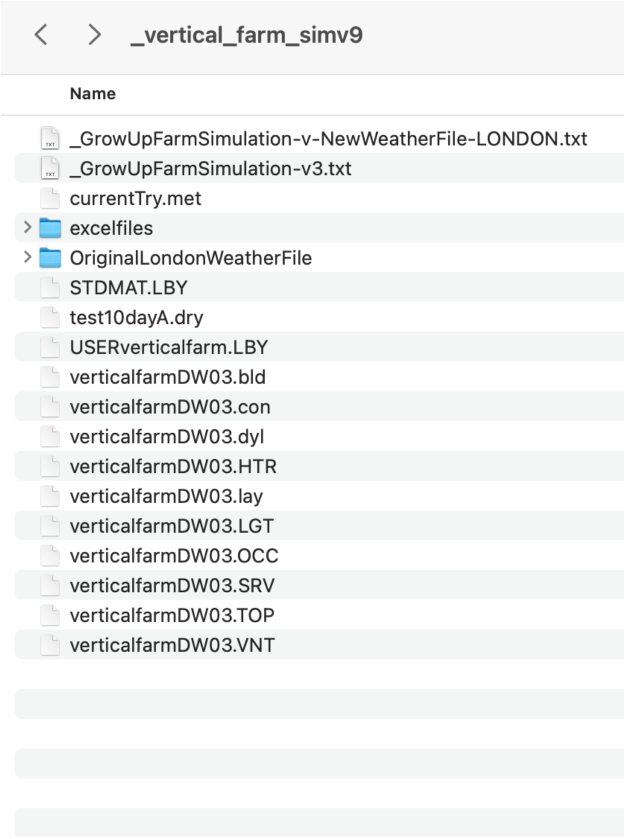
- _PhD
- _vertical_farm_other_files
- _vertical_farm_simv0-GrowUpFarm-OriginalData
- _vertical_farm_simv3
- _vertical_farm_simv4
- _vertical_farm_simv5
- _vertical_farm_simv6
- _vertical_farm_simv7
- _vertical_farm_simv8
- _vertical_farm_simv9
- _vertical_farm_simv9-ComparedMonitoringData
- _vertical_farm_simv9-RESULTS
- Additional_setup_files_for_THERM_v4
- Autodesk
- BACK UP SIM
- CPD
- data

tweak some of the parameters and understand the behaviour and validity of this simulation framework, in the context of vertical farms. Each different simulation helped to inform the next iteration until there was more clarity on how to analyse the data obtained from HTB2 in a truly comparative manner with monitored data from the real vertical farm. This was not a simple process of outputs and inputs, the modularity of HTB2 has been utilised to tailor the simulation to these specific scenarios.

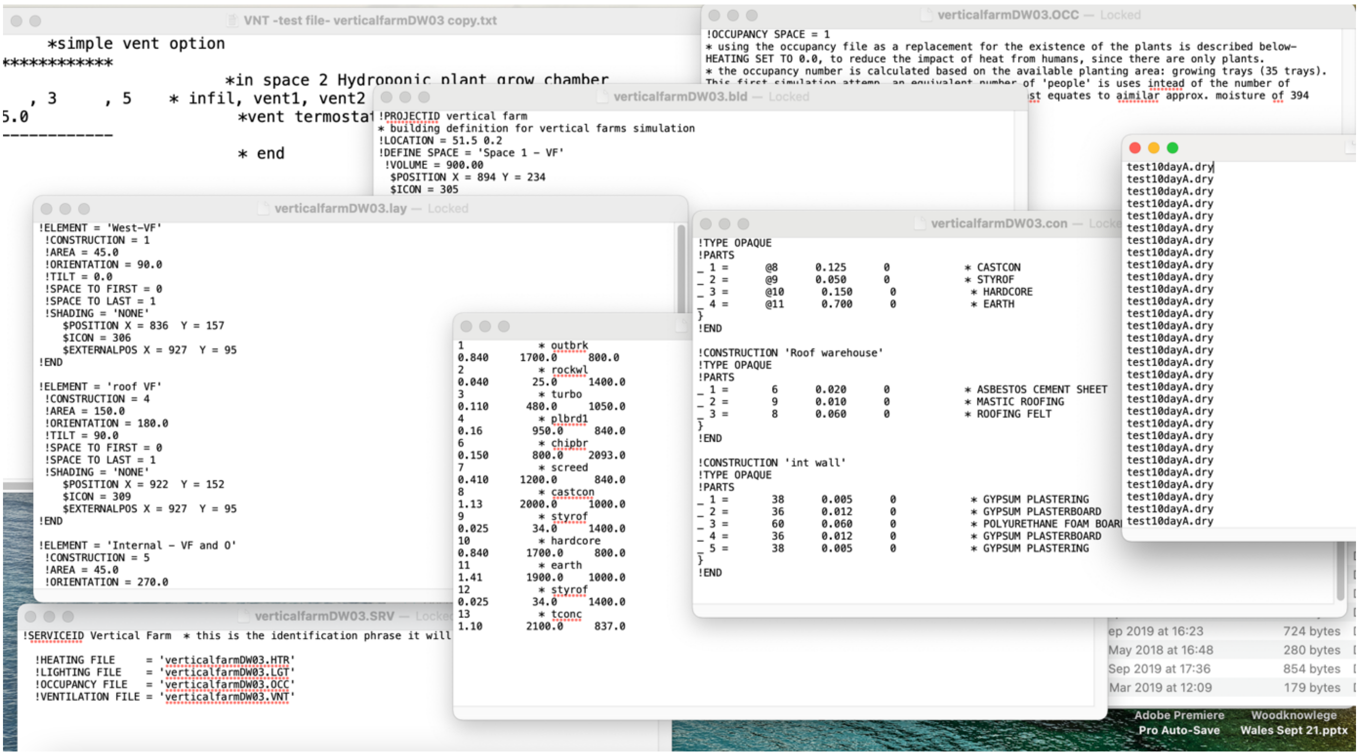
Since HTB2 has not been designed originally to develop this kind of scenarios, that outputs from the simulation had to extracted by hand from HTB2, transferred into Excel for the author of this work to develop the statistical analysis and other comparative studies to obtained the results that are part of this PhD Thesis.

This image to the right, is a sample view of the contents of one of the simulation folders, shown in the previous image. Here, most of the files are the HTB2 module, which are where all the data necessary to run each simulation is contained.

The image on the next page provides a snapshot of how several of these files (on the right, the HTB2 files) look like when they are open.



_GrowUpFarmSimulation-v-NewWeatherFile-LONDON.txt
_GrowUpFarmSimulation-v3.txt
currentTry.met
excelfiles
OriginalLondonWeatherFile
STDMAT.LBY
test10dayA.dry
USERverticalfarm.LBY
verticalfarmDW03.bld
verticalfarmDW03.con
verticalfarmDW03.dyl
verticalfarmDW03.HTR
verticalfarmDW03.lay
verticalfarmDW03.LGT
verticalfarmDW03.OCC
verticalfarmDW03.SRV
verticalfarmDW03.TOP
verticalfarmDW03.VNT



```
    *simple vent option
************
                         *in space 2 Hydroponic plant grow chamber
  , 3     , 5    * infil, vent1, vent2
5.0                       *vent termostat
------------
                          * end
```

```
!OCCUPANCY SPACE = 1
* using the occupancy file as a replacement for the existence of the plants is described below-
HEATING SET TO 0.0, to reduce the impact of heat from humans, since there are only plants.
* the occupancy number is calculated based on the available planting area: growing trays (35 trays).
This first simulation attemp  an equivalent number of 'people' is uses intead of the number of
st equates to aimilar approx. moisture of 394
```

```
!PROJECTID vertical farm
* building definition for vertical farms simulation
!LOCATION = 51.5 0.2
!DEFINE SPACE = 'Space 1 - VF'
 !VOLUME = 900.00
  $POSITION X = 894 Y = 234
  $ICON = 305
```

```
!ELEMENT = 'West-VF'
 !CONSTRUCTION = 1
 !AREA = 45.0
 !ORIENTATION = 90.0
 !TILT = 0.0
 !SPACE TO FIRST = 0
 !SPACE TO LAST = 1
 !SHADING = 'NONE'
    $POSITION X = 836  Y = 157
    $ICON = 306
    $EXTERNALPOS X = 927  Y = 95
!END

!ELEMENT = 'roof VF'
 !CONSTRUCTION = 4
 !AREA = 150.0
 !ORIENTATION = 180.0
 !TILT = 90.0
 !SPACE TO FIRST = 0
 !SPACE TO LAST = 1
 !SHADING = 'NONE'
    $POSITION X = 922  Y = 152
    $ICON = 309
    $EXTERNALPOS X = 927  Y = 95
!END

!ELEMENT = 'Internal - VF and O'
 !CONSTRUCTION = 5
 !AREA = 45.0
 !ORIENTATION = 270.0
```

```
1              * outbrk
0.840    1700.0      800.0
2              * rockwl
0.040      25.0     1400.0
3              * turbo
0.110     480.0     1050.0
4              * plbrd1
0.16      950.0      840.0
6              * chipbr
0.150     800.0     2093.0
7              * screed
0.410    1200.0      840.0
8              * castcon
1.13     2000.0     1000.0
9              * styrof
0.025      34.0     1400.0
10             * hardcore
0.840     1700.0     800.0
11             * earth
1.41      1900.0    1000.0
12             * styrof
0.025      34.0     1400.0
13             * tconc
1.10      2100.0     837.0
```

```
!TYPE OPAQUE
!PARTS
_ 1 =      @8      0.125      0             * CASTCON
_ 2 =      @9      0.050      0             * STYROF
_ 3 =      @10      0.150      0             * HARDCORE
_ 4 =      @11      0.700      0             * EARTH
}
!END

!CONSTRUCTION 'Roof warehouse'
!TYPE OPAQUE
!PARTS
_ 1 =       6      0.020      0             * ASBESTOS CEMENT SHEET
_ 2 =       9      0.010      0             * MASTIC ROOFING
_ 3 =       8      0.060      0             * ROOFING FELT
}
!END

!CONSTRUCTION 'int wall'
!TYPE OPAQUE
!PARTS
_ 1 =       38      0.005      0             * GYPSUM PLASTERING
_ 2 =       36      0.012      0             * GYPSUM PLASTERBOARD
_ 3 =       60      0.060      0             * POLYURETHANE FOAM BOAR
_ 4 =       36      0.012      0             * GYPSUM PLASTERBOARD
_ 5 =       38      0.005      0             * GYPSUM PLASTERING
}
!END
```

```
test10dayA.dry
test10dayA.dry
test10dayA.dry
test10dayA.dry
test10dayA.dry
test10dayA.dry
test10dayA.dry
test10dayA.dry
test10dayA.dry
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test10dayA.dry
test10dayA.dry
test10dayA.dry
test10dayA.dry
```

```
!SERVICEID Vertical Farm  * this is the identification phrase it will

  !HEATING FILE     = 'verticalfarmDW03.HTR'
  !LIGHTING FILE    = 'verticalfarmDW03.LGT'
  !OCCUPANCY FILE   = 'verticalfarmDW03.OCC'
  !VENTILATION FILE = 'verticalfarmDW03.VNT'
```

```
ep 2019 at 16:23       724 bytes
May 2018 at 16:48      280 bytes
Sep 2019 at 17:36      854 bytes
Mar 2019 at 12:09      179 bytes
```