SCHOOL OF ENGINEERING

PH.D. THESIS

A Decision Support System for Economic Viability and Environmental Impact Assessment of Vertical Farms

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Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor in Philosophy in Engineering.

by

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UNIVERSITY OF LIVERPOOL

DEDICATION

For my grandmother, Mamine. Her graciousness and love of nature continue to inspire me. This research is my wholehearted effort to protect our planet's ecosystems and harmonise technological advancements with Mother Nature.

Acknowledgements

After many ups and downs, twists and turns, I am beyond delighted to submit this thesis after five years. As with all things in life, I couldn't have done it alone.

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Declaration of Academic Integrity

Student Number	**200887831**
School/Institute	**School of Engineering**
Title of Work	**A Decision Support System for Economic Viability and Environmental Impact Assessment of Vertical Farms**

STUDENT DECLARATION

I confirm that:

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- I have acted honestly, ethically and professionally in conduct leading to assessment for the programme of study.
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- Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor in Philosophy by Francis José Baumont de Oliveira.

I declare Chapter 2, Literature Review, of this thesis has been released as a preprint on ResearchGate, 2022, as "A Typology Review of Vertical Plant Farms: Classifications, Configurations, Business Models and Economic Analyses".

I declare Chapter 3, Decision Support System Framework, of this thesis has been published in the *International Journal of Decision Support System Technology*, Vol. 13, Issue No. 1, pp. 34-66, 2021, as “A Collaborative Decision Support System Framework for Vertical Farming Business Developments” with co-authors Scott Ferson (primary supervisor) and Ronald Dyer (secondary supervisor).

I declare Chapter 4, Lessons Learned Interview Study, of this thesis has been submitted for publication in chapter 5 of the book *Advances in Plant Factories: New Technologies in Indoor Vertical Farming*, Editors Prof Toyoki Kozai and Dr Eri Hayashi, Burleigh-Dodds Publishing, as “Lessons Learned from Operating and Shuttered Vertical Farms” with co-author Ronald Dyer (secondary academic supervisor).

I declare Chapter 5, Lean Principles, of this thesis has been published in *Procedia CIRP*, Vol. 93 as “Lean Principles in Vertical Farming: a Case Study” with co-authors Hannah Forbes (directional advice and editing), Dirk Schaefer (academic supervision), and Jelena Milisavljevic Syed (academic supervision). This was presented at the *53rd CIRP Conference on Manufacturing Systems 2020*.

I declare Chapter 6, Financial Risk Assessment, of this thesis has been published in *Sustainability,* Vol. 14, Issue No. 9, pp. 5676, 2022 as “How High is High Enough? Assessing Financial Risk of Vertical Farms using Imprecise Probabilities” with co-authors Scott Ferson (primary supervisor), Ronald Dyer (secondary supervisor), Jens Thomas (industry supervisor), Paul Myers (industry supervisor), and Nicholas Gray (Python PBA risk package developer).

I declare Chapter 7, Environmental Impact Assessment, of this thesis has been accepted for publication in *Acta Horticulturae, 2023,* as “Pathways to Net-Zero Farming: a Carbon Footprint Comparison of Vertical Versus Traditional Agriculture” with co-authors Sam Bannon (experimental set-up), Luke Evans (guidance on hydrogen fuel-cell operation), Laurence Anderson (guidance on experimental set-up), Paul Myers (industry supervisor), and Jens Thomas (industry supervisor). This was presented at the International Society for Horticultural Science's International Symposium on Advances in Vertical Farming 2022

I declare Chapter 8, Drivers for Decision Support System Adoption in Agriculture, of this thesis has been published in the *International Journal of Decision Support System Technology*, Vol. 15, Issue No. 2, 2023, as “Design Thinking and Compliance as Drivers for Decision Support System Adoption in Agriculture” with co-authors Alejandro Fernández (secondment supervisor), Mariana del Pino (guidance on compliance and beta-tester of software), and Jorge E. Hernández (strategic oversight).

SIGNATURE: F. Beaumont

DATE: 30th November 2022

ABSTRACT

Vertical farming (VF) is the practice of growing crops or animals using the vertical dimension via multi-tier racks or vertically inclined surfaces. In this thesis, I focus on the emerging industry of plant-specific VF. Vertical plant farming (VPF) is a promising and relatively novel practice that can be conducted in buildings with environmental control and artificial lighting. However, the nascent sector has experienced challenges in economic viability, standardisation, and environmental sustainability. Practitioners and academics call for a comprehensive financial analysis of VPF, but efforts are stifled by a lack of valid and available data.

A review of economic estimation and horticultural software identifies a need for a decision support system (DSS) that facilitates risk-empowered business planning for vertical farmers. This thesis proposes an open-source DSS framework to evaluate business sustainability through financial risk and environmental impact assessments. Data from the literature, alongside lessons learned from industry practitioners, would be centralised in the proposed DSS using imprecise data techniques. These techniques have been applied in engineering but are seldom used in financial forecasting. This could benefit complex sectors which only have scarce data to predict business viability.

To begin the execution of the DSS framework, VPF practitioners were interviewed using a mixed-methods approach. Learnings from over 19 shuttered and operational VPF projects provide insights into the barriers inhibiting scalability and identifying risks to form a risk taxonomy. Labour was the most commonly reported top challenge. Therefore, research was conducted to explore lean principles to improve productivity.

A probabilistic model representing a spectrum of variables and their associated uncertainty was built according to the DSS framework to evaluate the financial risk for VF projects. This enabled flexible computation without precise production or financial data to improve economic estimation accuracy. The model assessed two VPF cases (one in the UK and another in Japan), demonstrating the first risk and uncertainty quantification of VPF business models in the literature. The results highlighted measures to improve economic viability and the viability of the UK and Japan case.

The environmental impact assessment model was developed, allowing VPF operators to evaluate their carbon footprint compared to traditional agriculture using life-cycle assessment. I explore strategies for net-zero carbon production through sensitivity analysis. Renewable energies, especially solar, geothermal, and tidal power, show promise for reducing the carbon emissions of indoor VPF. Results show that renewably-powered VPF can reduce carbon emissions compared to field-based agriculture when considering the land-use change.

The drivers for DSS adoption have been researched, showing a pathway of compliance and design thinking to overcome the 'problem of implementation' and enable commercialisation. Further work is suggested to standardise VF equipment, collect benchmarking data, and characterise risks. This work will reduce risk and uncertainty and accelerate the sector's emergence.

Keywords: *Vertical plant farming, plant factories with artificial lighting, financial forecasting, indoor farming, environmental impact assessment, probability bounds analysis, decision support system, lean manufacturing, lessons learned, risk assessment, uncertainty quantification.*

LIST OF PUBLICATIONS

PEER-REVIEWED JOURNAL PUBLICATIONS

1. Francis Baumont de Oliveira, Scott Ferson, and Ronald Dyer. A Collaborative Decision Support System Framework for Vertical Farming Business Developments. *International Journal of Decision Support System Technology*, 13 (1), 34-66, 2021.
2. Francis Baumont de Oliveira, Scott Ferson, Ronald Dyer, Jens Thomas, Paul Myers, and Nicholas Gray. How High is High Enough? Assessing Financial Risk for Vertical Farms Using Imprecise Probability. *Sustainability* 14(9), 5676, 2022.
3. Francis Baumont de Oliveira, Alejandro Fernández, Mariana del Pino, and Jorge E. Hernández. Design Thinking and Compliance as Drivers for Decision Support System Adoption in Agriculture. *International Journal of Decision Support System Technology 15(2), 2023.*
4. Nicholas Gray, Scott Ferson, Marco de Angelis, Ander Gray, and Francis Baumont de Oliveira. Probability Bounds Analysis for Python. *Software Impacts*. 12, 2022.

PEER-REVIEWED BOOK CHAPTERS

1. Francis Baumont de Oliveira and Ronald Dyer. Lessons Learned from Shuttered and Operating Vertical Plant Farms. *Advances in Plant Factories: New Technologies in Indoor Vertical Farming*, 2023 (In Press).
2. Alejandro Fernandez, Andres Marconi, Mariana del Pino, and Francis Baumont de Oliveira. GAP-a-Farm: A Tool to Support GAP Compliance and Information Based Decision Making in Horticulture. *RUC-APS Springer Book Volume 2*. 2022.

PEER-REVIEWED CONFERENCE PROCEEDINGS

1. Francis Baumont de Oliveira and Scott Ferson. Methodology for a Risk Assessment Decision Support System in Vertical Farming. *Proceedings of 5th International Conference on Decision Support System Technology 2019 on "Decision Support Systems: Main Developments & Future Trends".* 2019.*
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2. Francis Baumont de Oliveira, Hannah Forbes, Dirk Schaefer, and Jelena Milisavljevic-Syed. Lean Principles in Vertical Farming: A Case Study. *Procedia CIRP*. 93, 712-717, 2020. Presented at the *53rd CIRP Conference on Manufacturing Systems, 2020 in Chicago, IL, USA.*
3. Francis Baumont de Oliveira, Andres Marconi, Mariana Del Pino, Alejandro Fernandez, and Jorge E. Hernandez. A Gateway for Technology Adoption in Agriculture: a Design- Thinking Approach for a Compliance Decision Support

System. *Proceedings of 6th International Conference on Decision Support System Technology 2020 on "Cognitive Decision Support Systems & Technologies"*. 2020.

4. Francis Baumont de Oliveira, Sam Bannon, Luke Evans, Paul Myers, Laurence Anderson, and Jens M. H. Thomas. Pathways to Net-Zero Farming: a Carbon Footprint Comparison of Vertical Versus Traditional Agriculture. Acta Horticulturae. 2023. (In Press). Presented at the *31st International Horticultural Congress 2022 in Angers, France for the International Symposium on Advances in Vertical Farming.*
5. Hannah Forbes, Dirk Schaefer, Ji Han, and Francis Baumont de Oliveira. Investigating Factors Influential on the Success of Social Product Development Initiatives. *Procedia CIRP*. 91, 107-112, 2020. Presented at the *30th CIRP Conference on Design, 2020 in Skukuza, South Africa.*

UNPUBLISHED WORKS

1. Francis Baumont de Oliveira. A Typology Review of Vertical Plant Farming: Classifications, Configurations, Business Models and Economic Analyses. 2022. Available as a preprint on *ResearchGate*.

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LIST OF ABBREVIATIONS

AI – Artificial Intelligence
AC – Alternating Current
AVF – Association of Vertical Farming
BTU – British Thermal Unit
CapEx – Capital Expenditure
CDF – Cumulative Distribution Function
CEA – Controlled Environment Agriculture
CEO – Chief Executive Officer
COGS – Cost of Goods Sold
COVID-19 – Coronavirus Disease caused by SARS-CoV-2 Virus
CO_2 – Carbon Dioxide
C/N – Carbon/Nitrogen
DB – Database
DC – Direct Current
DESA – Department of Economic and Social Affairs
DFT – Deep Flow Technique
DSS – Decision Support System
DWC – Deep Water Culture
EC – Electrical Conductivity within the Nutrient Solution
ERP – Enterprise Resource Planning
FAO – Food and Agriculture Organisation of the United Nations
FIFO – First-In First-Out
GAP – Good Agricultural Practice
GE – Gas Exchange
GHG – Greenhouse Gas
GPL – General Public License
GUI – Graphical User Interface
HACCP - Hazard Analysis and Critical Control Point
HE – Heat Energy
HPS – High-Pressure Sodium
HVAC – Heating, Ventilation and Air-Cooling
IDEA – Investigate, Discuss, Estimate, and Aggregate
IoT – Internet-of-Things
IPCC – Intergovernmental Panel on Climate Change
IT – Information Technology
IVF – Indoor Vertical Farm

JIT – Just-in-Time
JPFA – Japan Plant Factory Association
KB – Knowledge Base
LED – Light Emitting Diode
MIT – Massachusetts Institute of Technology
ML – Model Library
MVP – Minimum Viable Product
m-PFAL – Micro- or Mini-Plant Factory
NASA – National Aeronautics and Space Administration
NFT – Nutrient Film Technique
NPV – Net Present Value
OpEx – Operational Expenditure
PAR – Photosynthetically Active Radiation
PF – Plant Factory
PFAL – Plant Factory with Artificial lighting
PFSL – Plant Factory with Solar Lighting
Vertical-PFSL – Plant Factory with Solar Lighting using Vertical Farming Systems
pH – Potential of Hydrogen
PPFD – Photosynthetic Photon Flux Density
ppm – Parts per Million
P-Box – Probability Box
QA – Quality Assessment
R&D – Research and Development
ROI – Return on Investment
RQ – Research Question
RUC-APS – Risk Uncertainty Collaboration for Agriculture Production Systems Project
SENASA – National Food Safety and Quality Service of Argentina
SOP – Standard Operating Procedure
SU – Space Utilisation
t – Radiation Transmittance
TA – Thematic Analysis
UA – Urban Agriculture
UI – User Interface
UN – United Nations
VF – Vertical Farming
VPF – Vertical Plant Farming
VSM – Value Stream Mapping

NOMENCLATURE

CO_{2f} – Carbon Dioxide Factor

CSR – Customer Share Ratio

F_r – Failure Rate

H_f – Humidity Factor

INS – Insolvency

L_f – Light Factor

N_f – Nutrient Factor

N_H – Number of Harvests.

N_p – Number of Plants

P_i – Plant Index

PI – Plant Income per Plant for a Customer Segment

P_p – Plant Price

PSR – Price Share Rate

R_f – Risk Factor

T_B – Threshold of Cashflow Becoming Negative

T_f – Temperature Factor

T_{ROI} – Threshold of ROI Specified by the User of the Software

Y_a – Adjusted Plant Yield

Y_s – Standard Plant Yield

CHAPTER 1

INTRODUCTION

"Agriculture makes people dependent on a few domesticated crops and animals instead of hundreds of wild food sources, creating vulnerability to droughts and blights and zoonotic diseases." – Robert M. Sapolsky, 2017 [1]

The Neolithic Revolution is thought to have begun 12,000 years ago, leading to a wide-scale transition of human culture from hunter-gather societies to agriculture and the rise of civilisation [2,3]. In the British Agricultural Revolution (between mid-17th and late 19th centuries), productivity increases were made possible due to mechanisation and better access to markets with transportation [4]. The Green Revolution (the 1960s-1980s) saw the use of hybridisation, genetic breeding, pesticides, and fertilisers [5]. The massive and seemingly boundless increases in food production made possible by these advances have enabled rapid global population growth. After the Green Revolution alone, the global population has increased by 5 billion people [6]. Expansion of agriculture and productivity have supported consumption and food availability, and without these accomplishments, many believe that famine and malnutrition would be widespread [7].

Over the centuries, the repercussions of such rapid growth, agricultural expansion and reduction of agricultural biodiversity have revealed themselves through severe damage to the Earth's environment and ecosystems [8]. The consequences are clearly visible: climate change, loss of natural ecosystems, soil degradation, water scarcity, excessive waste, and destruction of wild biodiversity. Understanding the role of agriculture in the functioning of our planet is not an academic exercise; the well-being and survival of humanity depend on it [8]. IPCC's Special Report on Climate Change (2019) estimates that up to 23% of all greenhouse gas (GHG) emissions are derived from agriculture and associated land-use change [9]. If pre- and post-production activities of the global food system are included, then the IPCC estimate its contribution to be up to 37% of GHG emissions [9]. Agriculture's GHG emissions significantly contribute to climate change [10], and the sector will be the first to suffer the consequences.

An imbalance in ageing rural populations could significantly impact global food production due to rapid urbanisation [11,12]. Food contamination also causes 420,000 deaths, 600 million cases of sickness, and a $95 billion USD loss in productivity every year globally [13]. Feeding a predicted 9.8 billion people by 2050, stressed by the aforementioned challenges, will require continuous innovation aligned to sustainable development goals to increase food production by 20-70% [14].

> *"Cities should learn to behave as ecosystems rather than parasites."* – Dickson Despommier 2013 [15]

A relatively new concept, vertical farming (VF) has become an increasingly popular method for food production. The concept is simple, to grow upwards rather than outwards. However, VF has many conflicting definitions in academia and industry [16,17].

In this thesis, VF is defined as "the activity or business of growing produce or animals using the vertical dimension via multi-tier racks or vertically inclined surfaces" [18]. The most common usage of the term "VF" is to describe vertical hydroponics systems, and when artificial lights are used instead of solar light, they are classified as indoor vertical farming [16]. However, the term vertical farm can also be used for the vertical production of mushrooms, insects, aquaculture or livestock [16]. When using plants specifically, the term vertical plant farming (VPF) is used. When VPF is used indoors, it has been labelled as plant factories with artificial lighting (PFAL) [16]. This thesis primarily focuses on PFALs using hydroponics to grow plants, with only a few exceptions where VF technology is used in a greenhouse set-up. In recent years, the practice has received substantial attention, with companies raising large rounds of investment due to its potential to engage with traditional agriculture's challenges.

The prerequisite technologies and knowledge that made modern VPF possible can be traced through horticultural history. Table 1.1 presents the chronology of milestones leading to the recent surge in vertical plant farms.

Table 1.1. Chronology of VPF-related projects, events, and prerequisite technologies

Milestone	Location	Year	Reference
Water-lifting irrigation devices	Ancient Egypt	≈ 1,500 BCE	[19,20]
Hanging Gardens of Babylon	Ancient Babylon	≈ 700 BCE	[21,22]
First recorded greenhouse	Italy	≈ 30 BCE	[23]
Chinese floating gardens	China	4th century	[19,20]
Chinampas of the Aztecs	Mexico	14th century	[19,20]
Artificial lighting	Global	19-21st century	[19,20]
Modernised greenhouses	Netherlands	19-21st century	[19,20]
Synthetic plastics	USA	1907	[3]
Vertical farming architectural sketches	Life Magazine, USA	1909	[24]
Soilless cultivation techniques	USA	1930s	[19,25]
Environmental control systems (growth chambers)	USA	1949	[3]
1st vertical hydroponic tower	Armenia	1951	[26]
Vertical greenhouse tower demonstration	Austria	1964	[24]
Japan's institutional research	Japan	1970s-1980s	[3,27,28]
Geniponics farm	USA	1973-1984	[29]
Phytofarms farm	USA	1978-1990	[29]
TS Farm by Kewpie	Japan	1983	[3,27]
Industrial factory PFAL	Netherlands	1984	[3]
NASA Bio-mass Production Chamber	USA	1987	[3]
Era of LEDs	Global	1990-current	[3]
Transition to LEDs in PFALs	Global	2005	[3]
Promotion of PFALs by the Japanese Government	Japan	2009	[27]
The boom of modern vertical plant farming	Asia, North America and Europe	2010-current	[27]

After the first architectural sketches of VF were published in 1909, it was not until the 1970s-1980s in Japan, the USA, and the Netherlands that the practice of VF was seriously investigated. The pioneers in these countries tested VF's feasibility in growing fresh produce for space exploration, extreme environments and even commercially [3]. These projects are the most akin to the modern VPF practised today—warehouse factories as opposed to ambitious skyscrapers. A few of the earliest projects were based in the USA. In 1973, Geniponics grew tomatoes, lettuce and cucumbers for nuclear submarines before shutting down in 1984 due to rising electricity costs [29]. Phytofarms operated a hydroponic assembly-line production within a two-storey warehouse between 1978-1990 but similarly closed due to energy costs, ageing lamps and excessive power consumption (1 MW per hour) [29]. Meanwhile, Japan's universities, research institutes and company labs conducted research and development into PFALs in the 1970s because of high urban densities [3,27,28]. Japan's research eventually led to the first commercial Japanese PFAL being launched in 1983 [30] and the operation of some of the longest standing vertical plant farms such as TS Farm by Kewpie Corporation [3,27]. These farms initially used high-pressure sodium (HPS) lighting before switching to fluorescent lighting by the late 1990s due to improved efficiency and reduced heat, tightening the space between the plant canopy and lights (from 1 m to 40 cm) and therefore increasing crop density [31].

Simultaneously, NASA began investigating controlled environment agriculture (CEA) to sustain bioregenerative human life support systems for space and converted one of their facilities in Kennedy Space Centre in 1987 for closed-system plant growth chamber experiments [3]. This was an important project due to the energy burden of the lights that proved unfeasible for spaceflight. Therefore, NASA sponsored the first plant research with light-emitting diodes (LEDs) technology in 1992, and the outcome was promising [3]. As a result, PFALs and indoor vertical plant farms began using LEDs as their light sources in 2005, catalysing the sector's growth due to the drastic energy efficiency improvements and reductions in operating costs. Meanwhile, consumer awareness of VPF and its benefits grew, mainly due to the research and promotional work from advocates like Toyoki Kozai and Dickson Despommier [19,32,33].

Nowadays, new farms are continuously being built in a diversity of sizes, locations, and business models. VPF commercial operations can range from 500 m^2 converted underground air raid shelters in London producing 60,000 kg of herbs [34] to 30,000 m^2 mega-PFAL in the Arabian desert producing 900,000 kg of leafy greens per year [35]. Although the popular ideas of skyscraper vertical farms in cities have been imagined, none have been commercially and economically realised [36–38]. Instead, indoor vertical farms have been placed in shipping containers, laboratories, supermarket shelves, restaurants, purpose-built and fully insulated warehouses, school basements, office building rooftops, and airports [18,38]. Businesses have targeted almost every customer segment imaginable: distribution, air transport, fitness, hospitality, hobby gardening, real estate, energy, and the list goes on [18,38]. VPF appeals to many businesses across sectors, as the underlying technologies in lighting, robotics, climate control, food processing, irrigation, energy management, and software are integrated into a unique food-water-energy nexus [39]. Fortunately, these technological advancements are continuously reducing VPF's high capital costs [40].

The number of vertical plant farms has surged over the past decade [41], with at least 3400 globally, including commercial, research, and micro-operations (see Figure 1.1). This value is based on confirmed farms from 2016-2021, and is likely to have fluctuated in the last couple of years. Many farms, including marijuana operations, are businesses in stealth mode; therefore they have been excluded. However, the VPF sector remains mostly unprofitable [42] and relatively tiny compared to field-based agriculture [43]. One estimate from a Rabobank analyst in 2020 claims the practice of VPF occupies the equivalent of 30 ha of land worldwide, compared to outdoor cultivation of 50 million ha and 500,000 ha for greenhouses [43]. The majority of the vertical plant farms are also small compared to the larger and more capital-intensive projects. Despite the touted benefits, the sector is still plagued by several defects and limiting factors inhibiting its wide-scale adoption, which will be explored in this dissertation.

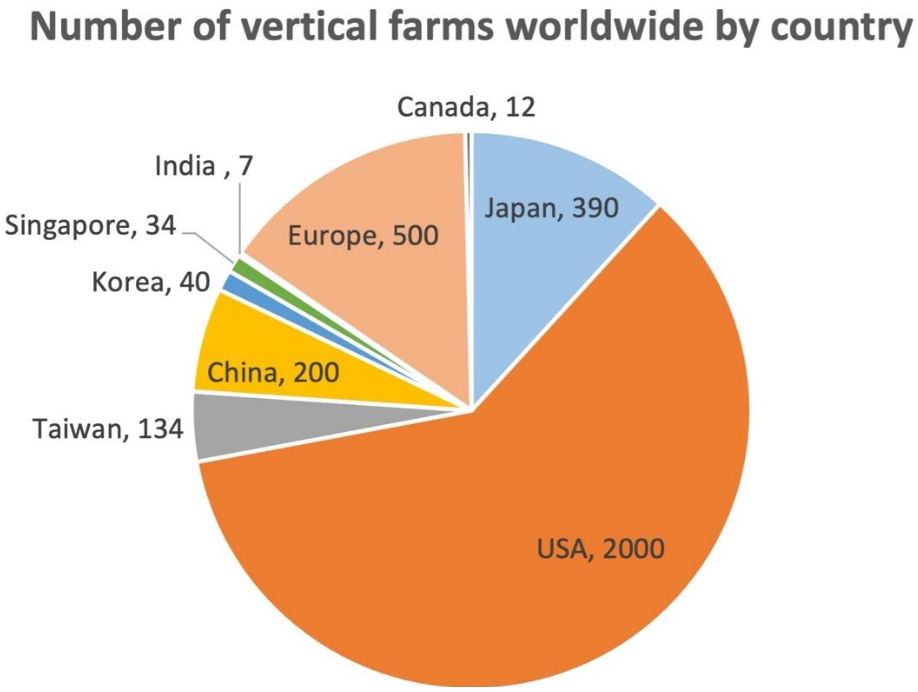

Figure 1.1. The lower estimate of number of vertical plant farms was collated from various sources [31,44–48]. There are likely many more farms operating on a micro-scale or in stealth mode. There are no estimates on the number of European VPF projects; therefore, a conservative estimate was generated based on a list of farms enumerated for this thesis.

By using indoor VPF techniques for horticulture, benefits can be realised compared to field-based agriculture:

1. Minimisation of horizontal space requirements and increase of yield per unit area [32,49].
2. Growing environment is unaffected by climate, solar light, or soil fertility; farms are location-independent and can be placed in tundras, deserts, zero-gravity environments, or built-up cities [19,32].
3. Produce can be pesticide-free, meaning crops do not need to be washed [32,41]
4. Reduction in water consumption by approximately 70%-95% [33,50,51] and potential to reuse wastewater [52].
5. Production can be all year-round crop at consistent quality and quantity [33]
6. Produce quality, such as concentrations of phytonutrients, can be manipulated through precise growing environmental control [32].
7. Reduction in the necessity for storage, transportation, and refrigeration through local production and smaller supply chains [33].
8. Increase in food safety through complete control over the production process, complete traceability, and reduced natural variables such as wildlife [33].
9. Increase in shelf life of perishables due to the bacterial load that is generally less than 300 colony forming units (1 to 0.1% of that of field-grown crops) [32].
10. Reduction of direct dependence on fossil fuels by operating electrically [33].
11. Enablement of rapid feedback cycles with reduced unknowns allows input-output optimisation, transfer of practical knowledge from lab to farm and accelerated crop breeding [19].
12. Contribution towards resilience from catastrophic events such as pandemics, supply-chain disruptions, nuclear fall-out, and natural disasters [19].

Alternative and more efficient food production methods are increasingly receiving attention for their capacity to provide resilience to a country's fresh food supply. Numerous shocks have disrupted agri-food supply chains over the past several years. In March 2020, the COVID-19 pandemic paralysed the world. The impact rippled through agri-food processes from field to consumer, highlighting the fragility of food security to consumers [53]. Temporary or seasonal work is typical, especially for planting, sorting, harvesting, processing or transporting crops to market [53]. Because many skilled workers could not access countries due to border controls, some countries made unsuccessful calls for unemployed people to work in agricultural fields [53]. Labour shortages were already a major issue before COVID-19, but the pandemic only amplified them [54]. These conditions retarded the delivery of food and agricultural inputs, causing challenges in continuous food supply to markets and may have caused irreversible changes to distribution [54]. Many complex factors have caused the rising tensions in agri-food supply chains: COVID-19, adverse weather, soaring input costs, inflation, and trade restrictions have sent food prices increasing steeply since 2020 [55,56].

In February 2022, Russia's invasion of Ukraine strained the global economy further, bringing the intertwined nature of the world's energy and food supply chains into sharp clarity and driving costs higher [57]. These two countries account for 30% of wheat production and play a crucial role in global fertiliser supply and fuel [58]. This has increased food, energy, and fertiliser prices [57,58]. The World Food Programme estimates that acute food insecurity has tripled between 2017 to 2021 and could increase by 17% because of the Ukraine crisis [59]. In addition, the invasion has affected Ukraine's ability to export agricultural products to feed 400 million people globally, causing an estimated $4.3 billion in agricultural damage [60]. These events spotlight the globally interconnected supply chains, food markets, and the associated inputs (labour, capital, fuel, fertiliser, electricity, and agrochemicals). It is evident that seemingly distant disruptions in one region or sector can have intense consequences for the rest of the world.

Tools like indoor vertical farms are needed to build agricultural resilience and buffer from the inevitable shocks such as climate change, labour shortages, geopolitical crises, and pandemics. The rising energy prices and costs of inputs will still impact indoor VF; however, diversification of food production reduces the potential of catastrophic risks to food security.

The sector must overcome the economic constraints of high capital costs and operating costs to enable VPF to contribute towards food security in any meaningful way. The costs reduce the pool of crops that can be sold at competitive prices to attract customers. Technically it is possible to grow any crop vertically, but most commercial farms have primarily dedicated their focus to crops that meet the economic threshold by converting the most light energy to edible matter, such as leafy greens, microgreens, and herbs. More recently, farms are commercially growing vine crops, bio-pharma ingredients, and small fruits [61,62]; however, these can have higher energy demands [63] and have added complexity with pollination. In Figure 1.2, the progression of crop feasibility with respect to commercial viability is illustrated. This progress will be complemented by crop breeding and genetic engineering specifically for indoor environments that can improve crop quality and reduce labour requirements [64,65]. Staple foods and root vegetables could have a higher impact on food security; however, their cultivation within commercial indoor VPF is not guaranteed due to much longer growing cycles and huge energy costs [66].

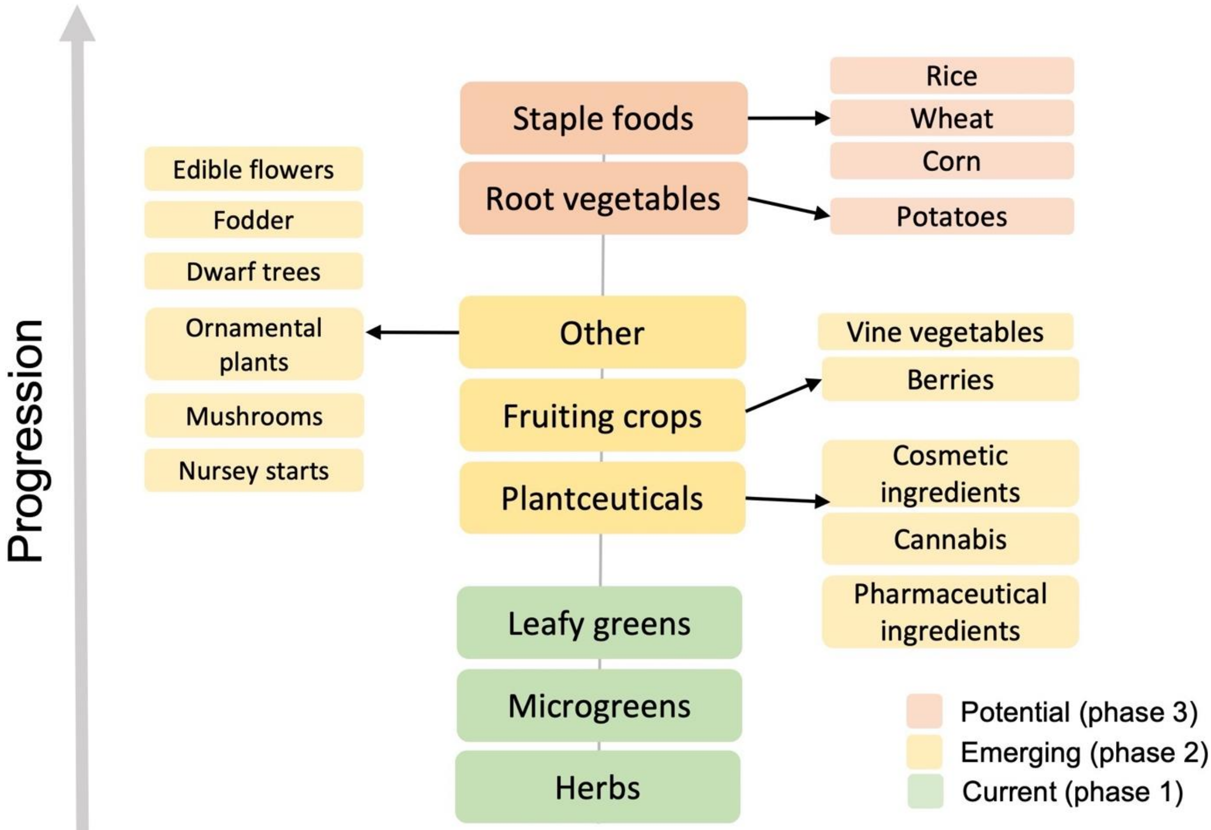

Figure 1.2. Crops categorised by commercial feasibility [19,67]

Over the years, the industry has witnessed some remarkable successes, but there has also been an overinflation of expectations caused by a combination of greenwashing, 'smoke and mirror' tactics, and favourable coverage in the media painting VPF as a panacea to our food system [40,68]. The reality is that the VPF is only one tool in humanity's toolkit to contribute toward food security and resilience, and it is not without its flaws. The sector is littered with failed start-ups that struggled to deliver on projected economics due to lack of quality labour, poor understanding of risk, and inappropriate use of technology [69]. There are no official records, but estimates indicate that roughly 85% of food-focused vertical farms fail within several years without further capital investment [70]. In addition, there have been high-profile and costly failures, for example:

- Local Garden, North America's first commercial vertical plant farm in the heart of Vancouver (2012-2014), went bankrupt and cost the city millions of dollars [71].

- MIT Media Lab's Open Ag Initiative (2015-2020) made fraudulent claims and promoted small vertical plant farm systems that did not work to attract investment [72].
- Plantagon International's $40 million 'World Food Building' (2012-2019) was a VF skyscraper which began construction but was never completed as the company declared bankruptcy [37].

"Most of us have been building farms whilst we've been operating them and that would be akin to building a plane whilst trying to take off; it's a recipe to crash." – Robert Colangelo, 2021 [73].

Information on profits have been elusive due to a scarcity of publicly available data [74–76], but practitioners report struggling to realise an acceptable return on investment (ROI) above 10% for investors [77,78]. Progress is slower than expected, as operators often must handle every aspect of the business, from new teams with no agricultural experience to developing distribution mechanisms for local delivery, researching and developing crop growth recipes and finetuning their technologies. Despite a sharp increase in investment over the past five years and billions of dollars in investment (see Figure 1.3), many farms have been unable to realise their ambitious expansion plans [40,68]. Companies require more time and knowledge to discover scalable pathways for VF, and the route to achieving this may not be as clear-cut as it initially appeared. Organisations are beginning to realise that collaboration may be critical for success [77,79,80], and academic research is needed to support the sector's emergence [30,76].

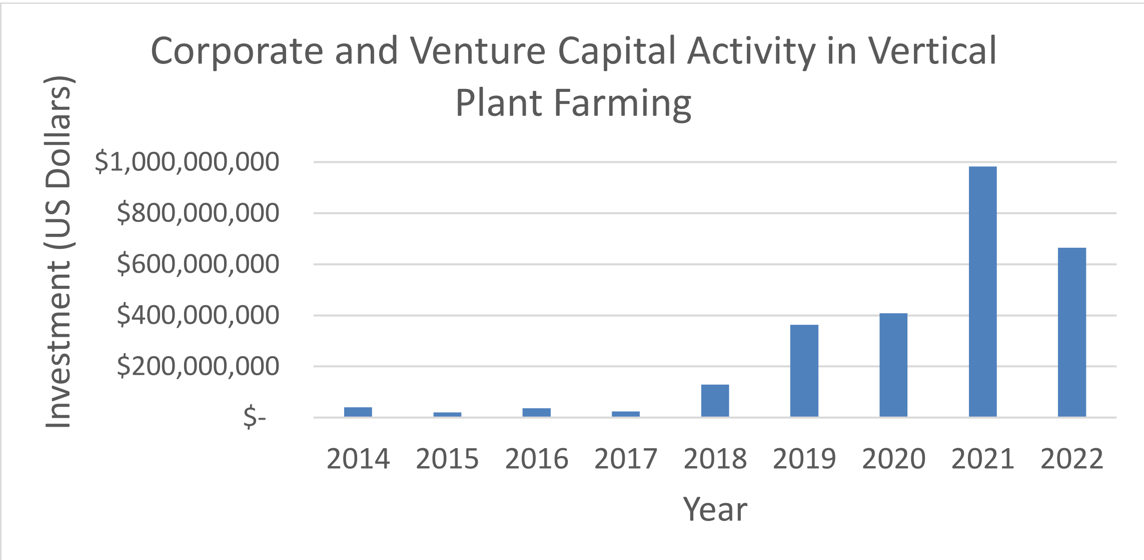

Figure 1.3. Investment deals in the vertical plant farming sector. Total investment since 2014: $2,670,000,000). Data accessed from i3connect.com with tag (vertical-farming): 7-10-2022 [81]

1.1 PROBLEM STATEMENT

To realise the economic viability and scalability of VPF, some core defects must be addressed (represented as interconnected factors in Figure 1.4). These inhibit the mainstream adoption of the practice and fuel much of its criticisms. This thesis will address these three constraints through interdisciplinary research engaged in industry contexts.

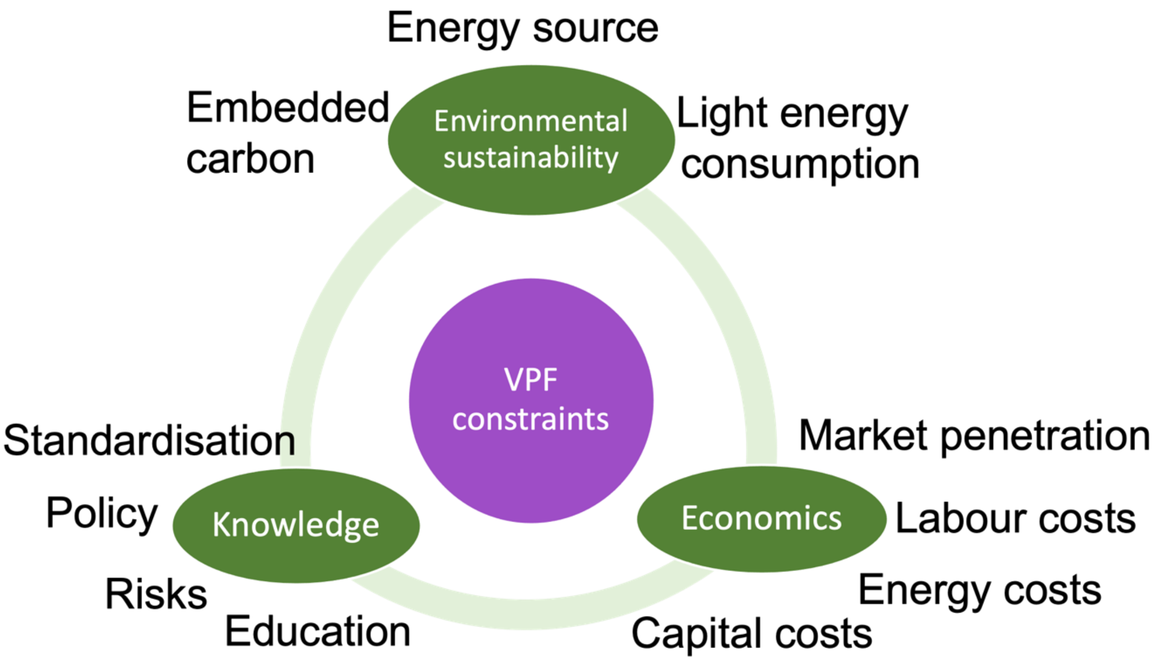

Figure 1.4. Key constraints to VPF adoption and scaling

Economic viability has been widely identified as a primary hurdle [75,76,82]. While prominent surveys have reported profitable operations [61,62], the financial risk is high due to unfavourable unit economics and considerable uncertainty, leading to funding being the top reported challenge for operators [61,75]. Detailed financial analyses of capital costs, operating costs, and revenues have been hard to produce due to the complex nature of combining architecture and agriculture with a lack of available data [75,76]. Moreover, labour, energy, and capital costs must be brought down through productivity and design improvements to reduce the high price of VPF produce and increase the ROI for investors.

To reduce the high number of promising new start-ups from falling at the first hurdle, there needs to be more accurate quantification of the economics of vertical farming and its derivatives using computer codes and detailed analysis. In addition, there is a need for a tool to help them estimate profit margins and the number of years to reach parity, incorporating risks from previous projects and using uncertainty to compensate for scarce data.

Many investors are concerned about the profitability of start-ups, and few creditors will make financial commitments without prospective financial data reflecting revenue and profit expectations [83]. However, they are beginning to recognise that vertical farms are a long-term play and require patient capital [73,78]. Providing a reliable tool for economic estimation for operators and investors could be beneficial in reducing barriers to entry.

Several systems are currently used for economic projections and estimations in VF; however, those available rely upon deterministic calculations, and there is currently no available tool that utilises stochastic methods to model financial uncertainty [36,75,84–86]. The drawbacks of these models are their lack of accuracy and repeatability in the real world. The main challenges are the lack of objective, quantifiable economic insight at a given time horizon and incorporating potential risks [75].

Despite many companies that tout claims of sustainability, the environmental impacts of indoor VPF should also be addressed with candour. Currently, the intensive energy consumption from artificial lighting using fossil-fuel-derived electricity and associated GHG emissions dwarf the direct GHG emissions from field-based agriculture and the greenhouse industry [87]. Indoor VPF may play an exciting role by contributing to the electrification of demand [88], whereby direct dependence on fossil fuels is minimised by using electricity instead to enable sustainable transitions. Different energy sources may hold opportunities to reduce the carbon footprint of indoor VPF [87,89]. Furthermore, if environmental concerns can be addressed, consumers may be more accepting of food grown indoors.

As this nascent sector is still novel compared to the 10,000-year history of field-based agriculture and 400 years of greenhouses, there are still significant gaps in knowledge, especially regarding terminologies, education, policy, risks and standards. There have been numerous commercial failures, yet no analysis examines why or the nature of the risks experienced. In addition, no literature regarding risk assessment in this sector has been conducted. Due to the complexity inherent in reverse-engineering nature's processes to grow plants indoors, the sector could benefit immensely from risk management guidelines and standardised metrics, data, and equipment. Efforts to achieve this could have a monumental impact on crop growth recipes and breeding due to the unprecedented rate of feedback cycles.

To provide effective support for decision-making, economic estimation, and environmental impact for vertical farms, researchers must admit that precise prediction of economics and business sustainability without available benchmarking and production data is unfeasible. There are too many parameters to optimise, too little available data, and no two farms are the same given different crops, markets, and climates. In part, the inability to create accurate business models, financial forecasts and risk management plans likely led to many entrepreneurs building farms without sufficient knowledge and closing down after several years.

The research questions (RQs) motivating the body of work contained in this thesis can be summarised as follows:

1. What technologies, configurations, and business models are being deployed by vertical plant farms?
2. What have been the limitations of economic analyses to date in addressing the economic viability of vertical plant farms?
3. What lessons can be learned from shuttered and operational VPF projects that could support developments?
4. What practical improvements can be made for labour efficiency to realise financial viability?
5. How can economic viability be modelled with a lack of available production and financial data?
6. What barriers inhibit vertical plant farms from scaling and acquiring funding, and how can these be overcome?
7. What are the characteristics of the risks and failure modes that result in the high failure rate of vertical plant farms?
8. What are the environmental impacts of vertical plant farms, and how can they be reduced?
9. What are the drivers for software adoption in agricultural communities?

1.2 Aim and Objectives

The research presented in this thesis aims to provide tools and strategies to overcome VF's challenges associated with economics, environmental sustainability, and risk assessment.

In doing so, the project will expose voids in academic knowledge and build a foundation for future research. This will be achieved through theoretical and computational solutions grounded in practical contexts. These tools will be developed in a decision support system, described later in this thesis, for operators and investors in running scenario analysis to manage risk, improve economic viability, and reduce negative environmental impacts. The project aim is subdivided into the following objectives:

- identify and classify VF configurations and business models;
- conduct a review of economic analyses applied to VPF;
- develop a decision support system framework that centralises the necessary information for risk-empowered business modelling to simplify economic estimation and enhance business sustainability;
- interview practitioners of VPF (operating and shuttered farms) to identify challenges, risks, opportunities and lessons;
- characterise failure modes and common risks of vertical plant farms so that they can be modelled;
- propose practical suggestions to achieve the labour efficiency benefits reported in the literature to aid economic viability;
- develop a prototype of the DSS using the conceptual framework to enable financial risk and economic viability and support current gaps in available data;
- introduce the concept of probability bounds analysis for adaptable economic modelling approaches to improve risk profiling and sensitivity analyses of start-up businesses;
- provide evidence-based case studies using the economic model to illustrate model robustness and validate potential efficacy to guide businesses interested in VPF opportunities;
- develop a carbon footprint life cycle assessment model with sensitivity analysis for VPF to encourage carbon-reducing practices; and
- examine reasons why practitioners may not have adopted similar tools.

1.3 Structure of Thesis

The research began in September 2017 and is presented within these chapters as a culmination of intertwined research articles linking to developing a decision support system (DSS) software to aid vertical farming business developments. The interdisciplinary research spans many fields, including software development, economics, risk management, environmental impact assessment, manufacturing systems, horticulture, and decision support. Many of the studies ran concurrently and are intended as an integrated study broadly spanning the requisite disciplines essential to elevate the feasibility of VF. The outcomes are a suite of practical tools for practitioners. The chapters have been presented in logical order for readability. Therefore, each chapter is introduced with a short section framing the article and how it connects to the overall research project. I hope the reader will enjoy this journey examining ways to realise the potential of VPF.

The first phase of research is presented in Chapter 2, focusing on the diverse array of VF configurations. The various configurations, classifications, business models and relevant economic analyses are reviewed. Before conducting interviews and developing generalisable software for economic viability, a typology was necessary to define clear definitions of the sector and evaluate the economic analyses conducted to date. This was absent from the literature.

Following the typology in Chapter 3, the decision support system framework and a risk analysis method are introduced. This provides an overview of the PhD project by describing the problems with the VPF practice (economics, environmental sustainability and standardisation) and proposing a software solution. Next, the methodology to conduct economic estimation and financial risk assessment informed by the views of farm operators is presented. The conceptual open-source framework is detailed with a specification of the knowledge library, database, and model library to inform prototype development. Illustrations of the user interface are also shown to build a complete picture of the software that would assist VF business developments. This chapter is an integration of all the methodologies in the chapters following it. The subsequent chapters cover different elements of the DSS framework alongside results from application to case studies.

Chapter 4 presents the results of the extensive interviews conducted over 4 years with a global range of operators, consultants, business owners, and researchers. Lessons learned from existing and shuttered VPF projects are deeply explored using mixed methods based on reflexive thematic analysis. The first complete risk register for this industry is a key result of this study. These interviews revealed many insights, most importantly, the lack of adequate and verifiable data that was planned to inform economic estimation and risk quantification. Economics and funding are reported to constrain the sector's growth, validating the market need for an economic estimation and risk analysis DSS.

In Chapter 5, labour, which is reported to be another main limiting factor of VPF economics, is addressed. Lean manufacturing system principles are applied in a VPF context by implementing strategies in a commercial case study. This exploratory study integrates these principles to show how substantial labour efficiency and cost savings can be made. The guidelines aim to inform how the DSS might suggest labour efficiency improvements.

The financial risk assessment methodology presented in Chapter 3 is refined and executed in Chapter 6. The open-source financial risk assessment software uses first-hitting-time survival modelling with imprecise probability. It was developed, coded, and applied to two industrial case studies: a semi-closed PFAL in Liverpool and a closed-PFAL in Japan. It was also used within the industry to inform decision-making and risk management for a farm in Liverpool. The proposed toolbox satisfies the requirements of entrepreneurs and investors who must estimate the feasibility of a project without access to reliable and relevant data. The reported risks from the interviews are integrated into the assessment. Finally, the results of the two use cases are presented and validated with operators.

Environmental impact assessment is the other aspect of the DSS to be explored. In Chapter 7, a flexible carbon life cycle analysis is described and used to compare traditional agriculture and VPF using an experimental farm. Sensitivity analysis for different energy types and the inclusion of deforestation and rewilding of different biomes are considered. This completes the final aspect of the DSS prototype.

As an additional study, Chapter 8 is the research conducted to understand how to enable developing countries to adopt high-tech solutions like DSSs and VF. The resulting study develops a software tool informed by design-thinking and compliance requirements to encourage technology adoption for greenhouse growers.

Each chapter is based on a research article containing its own literature review and methodology. In Chapter 9, the conclusions and future works then summarise the findings from the preceding chapters alongside the culmination of the work through the lens of the proposed software prototype.

1.4 Summary of Original Contributions

The main result of this body of work is a novel computational model for risk analysis and economic estimation for a new and complex emerging industry (Chapter 6). This tool realises the integration of approaches (probability bounds analysis, financial forecasting, and first-hitting-time survival modelling) which have not been used before in an investment or indoor farming context. Moreover, uncertainty quantification and risk assessment have never been applied to the VF sector. Economic analyses conducted previously are inaccurate and utilise unverified data or data from greenhouses which cannot be extrapolated to VPF production. This model allows users to calculate economics without making overly precise assumptions and with the flexibility to consider various system types. Furthermore, the model offers scenario testing to aid users in their decision-making, which was validated and tested by operators. The original algorithms for these models are provided to extend the applicability of probability bounds analysis to other contexts and fuel further research and use cases in indoor farming.

For labour, no actionable research existed on how labour efficiency improvements can be made despite reports of labour cost savings of 50% from some operators and researchers. In industry circles, there were conversations about the applicability and importance of manufacturing principles because of PFAL's similar characteristics to factories; however, the application of such principles in the literature was missing. The research applying lean principles to VF was the first article (Chapter 5) to demonstrate the integration of these ideas into VF and has been applied by readers and operators since.

There have been claims that VPF is a business riddled with risk and uncertainty, yet no efforts to list all the risks facing vertical agricultural production have been presented. Moreover, many projects are known to fail after several years, and discussion on reasons for failure and lessons learned remains absent in the academic literature. In the interview study (Chapter 4), a collation of practitioners' anecdotal experiences provides a comprehensive list of risks and insight into economics, labour, growing, labour, technology, and strategy. Academic research has propelled a surge in VPF projects; however, there is a lag between industry practitioners. The industry has invested considerable capital in research and development (R&D), which has not necessarily been recirculated into academic communities. This lessons learned study reveals their honest experiences highlighting practical advice and research areas of high impact, such as labour efficiency, cost-benefit analysis, growing experience, and validated production data.

The environmental impact of indoor VPF is a core criticism; however, the opportunities to use various renewable energies and consider the indirect and hidden impacts of traditional agriculture have not been quantified or explored. Our study was the first to conduct a carbon life cycle analysis of an indoor VF that considers sensitivity analysis of various energy types and rewilding as a path to net-zero carbon farming.

This thesis can be seen as the first investigation of risk assessment and manufacturing principles in the field of vertical farming, with methods developed that can be used for other emerging sectors.

CHAPTER 2

LITERATURE REVIEW

FRAMING

In this review, I redefine and understand the terminologies associated with vertical farming, which have been ambiguous due to the lack of consensus amongst practitioners and researchers. Furthermore, I review the classifications, configurations, and business models discussed in academia and industry, aiming to synthesise them.

To inform the standardisation and aggregation of data, there must first be an interpretation of the definitions and differences between farms. In this synthesis, I provide a typology based on my understanding and experience after five years of research. As this chapter was written last, my understanding has evolved with the industry. For example, I think the term 'plant factory with artificial lighting' more accurately depicts vertical plant farms, whilst a 'vertical farm' encompasses all food production in multiple tiers. The reader may notice some discrepancies in proceeding chapters 3 to 8 (written in 2019-2022), but I reflect on my current understanding and the latest research in this chapter (late 2022). I decided to keep 'vertical farming' in the thesis title as the methods described could be transferred easily to other food types grown using the vertical dimension.

Following the typology, I examined the economic models that informed Chapters 3 and 6. I found many issues and research gaps through verifying the analyses. I had to summarise these findings due to journal scope limitations. The content of the review has been adapted to include recent literature. Therefore, this chapter will include the original material and background research with updated analyses applied to vertical plant farming projects.

This literature review was released as a preprint on ResearchGate [18] and is available at http://doi.org/10.13140/RG.2.2.24729.49766/2 (accessed: 30th November 2022).

F.B.D.O was the sole author of this study.

A Typology Review of Vertical Plant Farms: Classifications, Configurations, Business Models and Economic Analyses

Available as a preprint on ResearchGate [18]

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2.1 Abstract

Vertical farming (VF) is the activity or business of growing produce or animals using the vertical dimension via multi-tier racks or vertically inclined surfaces, typically in and around densely populated areas. VF is primarily known in the context of growing plants; this can be called vertical plant farming (VPF). Successful scaling of VPF as a part of mainstream agriculture requires numerous improvements in public policy, consumer acceptance, and economic viability. To upscale the practice, socio-economic, research and policy-related institutions must work together. VPF terminologies are novel and complex, with conflicting definitions in the literature. This makes international and inter-disciplinary collaboration challenging. In this review, VF classifications are centralised before focusing on VPF configurations and business models to form a taxonomy. The VPF taxonomy can identify and classify any vertical plant farm. Finally, the economic analyses in the literature are examined and critiqued, classifying the case studies according to the typology. More data and research is required to advance the economics research of VPF and help realise its potential of seriously contributing to food security and resilience.

2.2 Introduction

Vertical farming (VF) is a relatively new practice of growing food using multi-tier racks or vertically inclined surfaces (such as walls). Vertical farms exist in many configurations, and there is no consensus on terminology [19]. This hinders communication for standardisation, research and development (R&D), and public policy developments which could help in upscaling the practice [16,19]. For example, the terms “indoor farm”, “plant factory with artificial lighting”, and “vertical farm” are sometimes used interchangeably [16,90,91]. Research is required to lay the foundation of the emerging sector and clarify the terms used.

Dickson Despommier, in 2010 popularised the term "vertical farming" as "the mass cultivation of plant and animal life for commercial purposes in skyscrapers" [33]. The use of vertical farms for growing a variety of food types is emphasised by other researchers [16,36,92]. Since 2010 there has been a surge of VF start-ups that have developed multi-tier food production in custom-built warehouses, disused buildings, rooftops, basements, containers, and more [19,93]. However, no companies have succeeded in creating the commercial skyscraper farms envisioned. Additionally, many VF practitioners focus on hydroponic plant production. Therefore, many researchers also discuss vertical farms solely in a plant context [19,75] but there are numerous examples of vertical multi-tier production of fish [94], insects [95,96], mushrooms [97], and livestock [98,99]. The term, vertical plant farming (VPF), could be used instead when focusing on plants.

Governments and policymakers have struggled categorising vertical farming operations, especially as they integrate a food-water-energy nexus in primarily urban environments. Simpson (2019) suggests that legal frameworks "do little to address the regulatory ambiguities faced by commercial scale, indoor farming operations, especially vertical farms" [100]. In many cases, VF appears to fall between policy areas and, under current definitions, is not considered agricultural or rural enough to access governmental subsidies [101].

For VPF, the economic analyses conducted to date have been sparse and mostly absent of real-life production and financial data [75]. The lack of benchmarking data has been a major contributing factor. For researchers and practitioners to make fair comparisons between different configurations and business models, there first needs to be clear definitions. Without such a typology, disparate economic analyses examine hypothetical facilities that range from grandiose skyscrapers [36], next-generation multi-storey facilities with multiple food types [102,103], to a vertical growing system in an apartment [90] under the same term 'vertical farming'. Currently, an apples-to-apples comparison is impossible. Other analyses compare hypothetical greenhouses vs vertical farms, which are either open or closed to the environment [85,91]. Such analyses sometimes paint VPF in a favourable yet perhaps unrealistic light which will be explained later in this review.

A review of vertical plant farm classifications, configurations, and business models is needed to centralise existing literature and aid policymakers and decision-makers in classifying VF projects. A typology would enable more international collaborations across academia, industry, and governments. Moreover, R&D efforts such as crop breeding and crop growth recipes may be accelerated by categorising datasets from varying farm types.

A review by Al-Kodmany (2018) looks at VF developments from an urban planning perspective to understand what defines 'VF' and comprehend its driving forces and implications [38]. Al-Kodmany also explored VF for peri-urban settings [104]. In 2022, Kozai discussed the terms related to PFALs [16] as an intended starting point to establish clear definitions. This review intends to follow on from those studies and addresses the following questions:

- What are the types of vertical farms in relation to classifications and configurations?
- What typology can be proposed to simplify classification?
- What are the existing business models for vertical farms?
- What are the economic analyses conducted on vertical farms, and their limitations?

This review is structured into five sections:

1. An overview of the terminologies and classifications of VF.
2. An overview of the different configurations and technologies used in VPF to form a taxonomy.
3. The current business models in operation within the VPF sector.
4. A comparison and critique of the economic analyses applied to VPF.
5. Conclusions and future works to use the typology to advance the sector.

2.3 CLASSIFICATIONS

The terms "vertical farm", "indoor farm", and "plant factory with artificial lighting" are often used interchangeably and increasingly within research papers, industry and mainstream media [16]. Figure 2.1 shows the increasing prevalence of these terms within the academic literature and the predominant use of "plant factory". There was a gradual increase in publications since 1970 before a surge after 2017, especially for the terms vertical and indoor farm. This can create misunderstandings, especially regarding data-sharing, scientific research, policy, and standardisation. R&D of vertical growing systems for various food types are emerging, and they too can be classified as "vertical farms". Moreover, facilities may use solar light and still be called a "plant factory" or a "vertical farm". What differentiates these terms? As this new sector begins to scale, precise terminologies and definitions are required to accelerate developments.

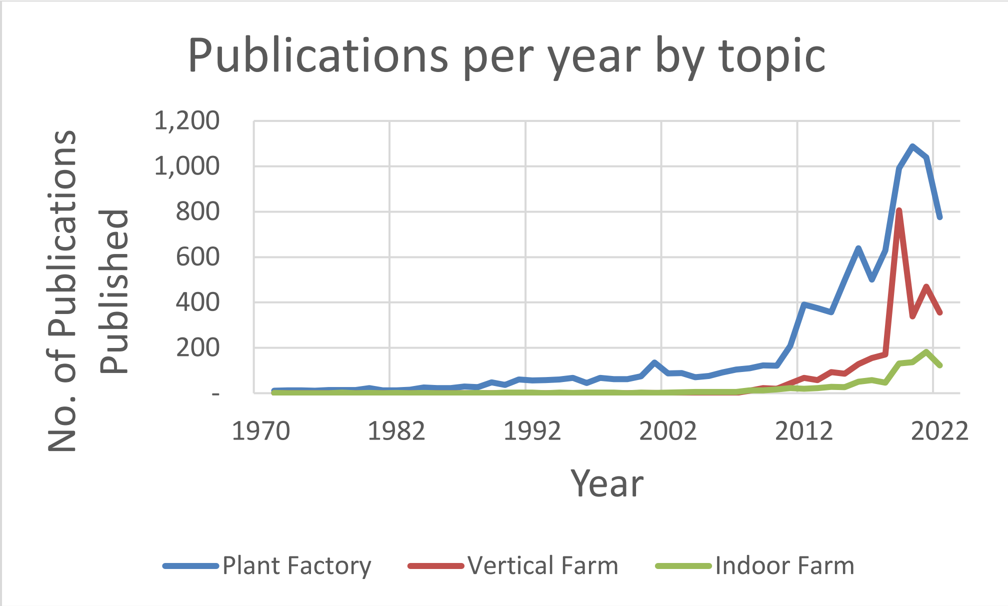


Figure 2.1. Annual trend of research publications on 'plant factory', 'vertical farm', and 'indoor farm' (total papers: 13,252). The 2022 data was taken in the third quarter, and will likely increase beyond previous years. [105] accessed on: 21st September 2022). Inspired by Kozai (2022) [16].

2.3.1 Vertical farming

Based on a collation of research, the definitions used for a vertical farm typically focus on plants in multi-tier closed environments without sunlight [38,106] or tall buildings for different crops [33,107]. Although many European and American researchers use these definitions, they are inadequate for capturing the breadth of existing VF projects. Many VF projects are not in closed environments [108,109], nor are they in tall buildings [31,110]. Based on English Oxford Languages Dictionary (2022) definitions for 'farm' and 'farming', more apt definitions for VF would be:

> *Vertical farming (verb) – "The activity or business of growing produce or animals using the vertical dimension via multi-tier racks or vertically inclined surfaces".*
>
> *Vertical farm (noun) - "An area of land and its buildings, used for growing crops or rearing animals using the vertical dimension via multi-tier racks or vertically inclined surfaces".*

In 2022, Kozai [16] explored the terms related to VF to establish their uses. He proposes a classification for VF according to food types in Table 2.1. A vertical plant factory with solar lighting is added to the classification to identify vertical plant farms that use solar lighting.

Table 2.1. Classification by vertical farm by produce type (Adapted from Kozai (2022) [16]).

Food type	Vertical farm type
Plants	Plant factory with artificial lighting (PFAL)
	Vertical plant factory with solar lighting (and optional supplemental lighting) (PFSL)
	Other vertical plant farm configurations (for example, outdoor vertical plant farms and green walls)
Insects	Vertical cricket/soldier fly farm
	Vertical silkworm farm
	Vertical earthworm factory, etc.
Aquaculture	Vertical fish farm
	Vertical shellfish farm
Animal	Vertical livestock farm
	Vertical poultry farm
Microorganism/fungus	Vertical mushroom farm
	Vertical fermentation farm
	Vertical sewage/waste processing farm
Combination of the above	Vertical hybrid farm

2.3.2 PLANT FACTORY

The first recorded use of the term 'Plant Factory' was in 1974 in Japan [16] to describe a factory-style facility for producing plants. According to Kozai [16], a plant factory was defined by M. Takatsuji in 1979 (translated from Japanese) *[28]*:

> *Plant factory (noun) – "A facility that enables scheduled and stable production of high-quality plants with the use of artificial and/or natural (or solar) light."* [16,111].

From 2010-2014, Japan's government provided subsidies for research, business and training in plant factories [16], increasing the adoption of these terms in other Asian countries [16]. The term plant factory was further differentiated for the use of solar lighting and artificial lighting. In Table 2.2, the definitions of the various types and sub-types of plant factories are collated from the literature. New labels are provided for the sub-categories: vertical-PFSL, open-PFAL, semi-closed-PFAL and closed-PFAL. The term "closed" in this context is used to describe the level of protection from external environmental influences (radiation, temperature, and gas exchange) and the degree of control (CO_2 enrichment and air-cooling). Three factors influence the degree of protection of the cultivation room that can be used to categorise PFALs relative to one another [112]:

1. Heat energy (HE): heat transmission coefficient of the walls, floor and ceiling ($J/m^2/s/°C$).
2. Gas exchange (GE): ventilation rate (m^3/hour) or the number of air exchanges per hour (h^{-1}) divided by the room air volume (m^3), including invasion of insects, dust, etc.
3. Radiation transmittance (t): transmittance of the walls/ceiling concerning photosynthetically active, ultra-violet, or thermal radiations. t = 0% means that no wave bands enter the structure.

Table 2.2. Plant factory classification

Plant factory type	**Definition**
Plant factory with solar lighting (PFSL)	PFSL - A Dutch-style greenhouse for growing plants with or without supplemental lighting, environmental control, and automated handling units. As defined by Japan's Ministry of Agriculture, Forestry and Fisheries [16]. $0.02 < GE < 60\ h^{-1}$. $HE > 1\ J/m^2/s/°C$. $t > 0\%$
	Vertical-PFSL – A PFSL that uses multi-layer systems, described by van Delden et al. 2021 as high-tech multi-layer greenhouses [19]. $0.02 < GE < 60\ h^{-1}$. $HE > 1\ J/m^2/s/°C$. $t > 0\%$
Plant factory with artificial lighting (PFAL)	PFAL - A special plant factory that exclusively uses artificial light to produce any plant. They contain a cultivation room and other areas for production activities (air shower, pre-cooling, dressing, packaging, shipping etc.) [113]. A cultivation room can have double-layer glass windows for visitors or workers to see into the growing area (still considered t = 0% so long as no solar light enters the building).
	Open-PFAL – Some environmental control but not air-conditioned, using natural or forced ventilation through openings covered with fine mesh nets to prevent insects [114]. $5 < GE < 20\ h^{-1}$ OR $2 < HE < 5\ J/m^2/s/°C$ AND t = 0% [115]
	Semi-closed-PFAL – partial environmental control with air conditioning by either air-cooling or water-cooling but uses some degree of natural ventilation and usually has no CO_2 enrichment [114]. $0.02 < GE < 5\ h^{-1}$ OR $0.15 < HE < 2\ J/m^2/s/°C$ AND t = 0%.
	Closed-PFAL – a highly airtight and thermally insulated structure with a closed plant production system (CPPS) for a cultivation room [116] and no use of pesticides. The CPPS has precise environmental controls equipped with air conditioners and CO_2 enrichment, allowing the consumption of crops without washing. Water vapour transpired by crops can be recycled to reduce water requirements. [114]. $GE \leq 0.02\ h^{-1}$ AND $HE \leq 0.15\ J/m^2/s/°C$ AND t = 0%. [115]

Micro- and mini-PFAL (m-PFAL)	m-PFAL - A small PFAL system set up for various purposes (i.e. home use, restaurants, shopping centres, schools, hospitals, etc.). *Micro-PFALs* range in growing volume from 0.03 m^2 to 1 m^3. *Mini-PFALs* range from a growing volume of 2 m^3 to 30 m^3. [114].
	Open-type m-PFAL (or desktop-type) – no environmental control except for artificial lighting [117]. $2 < GE < 20\ h^{-1}$ OR $1 < HE < 5\ J/m^2/s/°C$ AND $t \approx 0$ %.
	Closed-type m-PFAL – A cabinet system with some environmental control, such as fans and pumps, but no air conditioner or CO_2 supply [117]. $0 < GE < 2\ h^{-1}$ OR $0.1 < HE < 1\ J/m^2/s/°C$. $t \approx 0$ %.
	Walk-in type m-PFAL – A small PFAL which a person can enter, usually with environmental control systems to control air temperature, lighting, CO_2, water, fertiliser, etc. [117]. $0 < GE < 2\ h^{-1}$ AND $0 < HE < 2\ J/m^2/s/°C$. : $t \approx 0$%.

PFALs and vertical-PFSLs practice VPF to maximise space within the cultivation room. The sub-types are not classified in "Terms related to PFALs" by Kozai [16] but allow for the classification of vertical plant farms that have otherwise been labelled as 'indoor vertical farms' or 'greenhouse vertical farms'. As these terms do not include plants, they can now be classified with enhanced accuracy. Due to the predominant use of "plant factory" terminology in the literature (see Figure 2.1), it is preferable to use these terms to replace indoor vertical plant farms. All the concepts of VPF have been classified into the categories described (see Figure 2.2).

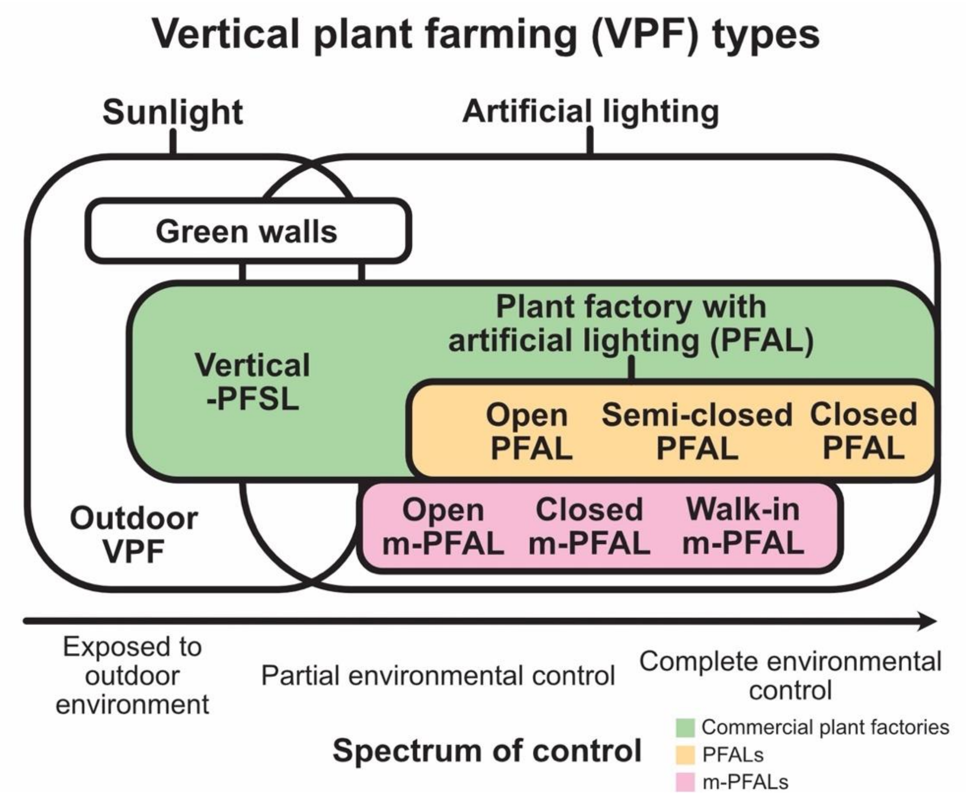


Figure 2.2. Vertical plant farm types by the spectrum of control and lighting type (cf. Kozai (2022) [16]).

2.3.3 Indoor Farming

Indoor farming is sometimes used to describe an indoor vertical farm or PFAL [16]. In a recent review, Stein (2021) defines indoor farming as " growing plants under controlled environmental conditions" [118]. Such a definition would encompass all controlled environment agriculture projects (CEA). According to Mitchell's historical overview of controlled environment horticulture (2022), CEA is the umbrella term that covers the appellations, including greenhouses, hoop houses, indoor farming, container farms, PFALs, and more [3]. Mitchell (2022) states that all the cardinal factors of plant growth (light, temperature, water, and atmosphere) must be provided and controlled to bring crops to maturity indoors [3]. Therefore, indoor farming would only be applicable where a farm is sheltered from light, excluding greenhouses, PFSL, and hoop houses. It is worth noting that mushroom farms have grown indoors and vertically for the past hundred years [119]. Moreover, indoor vertical farms are sometimes built into shipping containers for growing plants [120], mushrooms [121] and fish [122]. Therefore, a reasonable assumption would be to use the term 'indoor farming" to include all produce types grown in structures with minimal influence from the outdoor environment as a subset of CEA. The following definition is proposed by combining "indoor" and "farming" from English Oxford Languages Dictionary (2022) with the understanding that no solar light is used:

> *Indoor farming (verb) – "The activity or business of growing produce or animals within a building or structure protected from solar lighting and external weather".*
>
> *Indoor farm (noun) - "An enclosed farm within a building or structure protected from solar lighting and external weather".*

2.3.4 Differentiating Agricultural Concepts

In this discourse, it has been established what 'vertical farming', 'plant factory', 'controlled environment agriculture', and 'indoor farming' mean. All of these concepts can overlap, which understandably creates some confusion. To add complexity, some researchers refer to VF or indoor farming projects as happening exclusively in cities and can label them 'high-tech urban agriculture' [123,124]. This can be explained by how the concept was initially envisioned by Despommier (2010), who popularised the term 'vertical farming' and argued the benefits of farming in high-rise buildings in dense urban environments [33]. However appealing it is to build vertical farms in city centres, the economics are not always favourable, with disproportionately high real estate costs. Increasingly, developers are building wholesale-focused vertical farms in peri-urban locations near points of distribution to minimise associated costs [69,78,104,125]. VF has exciting potential in urban environments, but keeping the concepts distinct and inclusive is essential. Urban agriculture (UA) depends on location, whilst CEA depends on the environment, and indoor farming is a subsect of that practice. VF is dependent on the layout of the farm equipment. A delineation of all the concepts mentioned is illustrated in Figure 2.3.

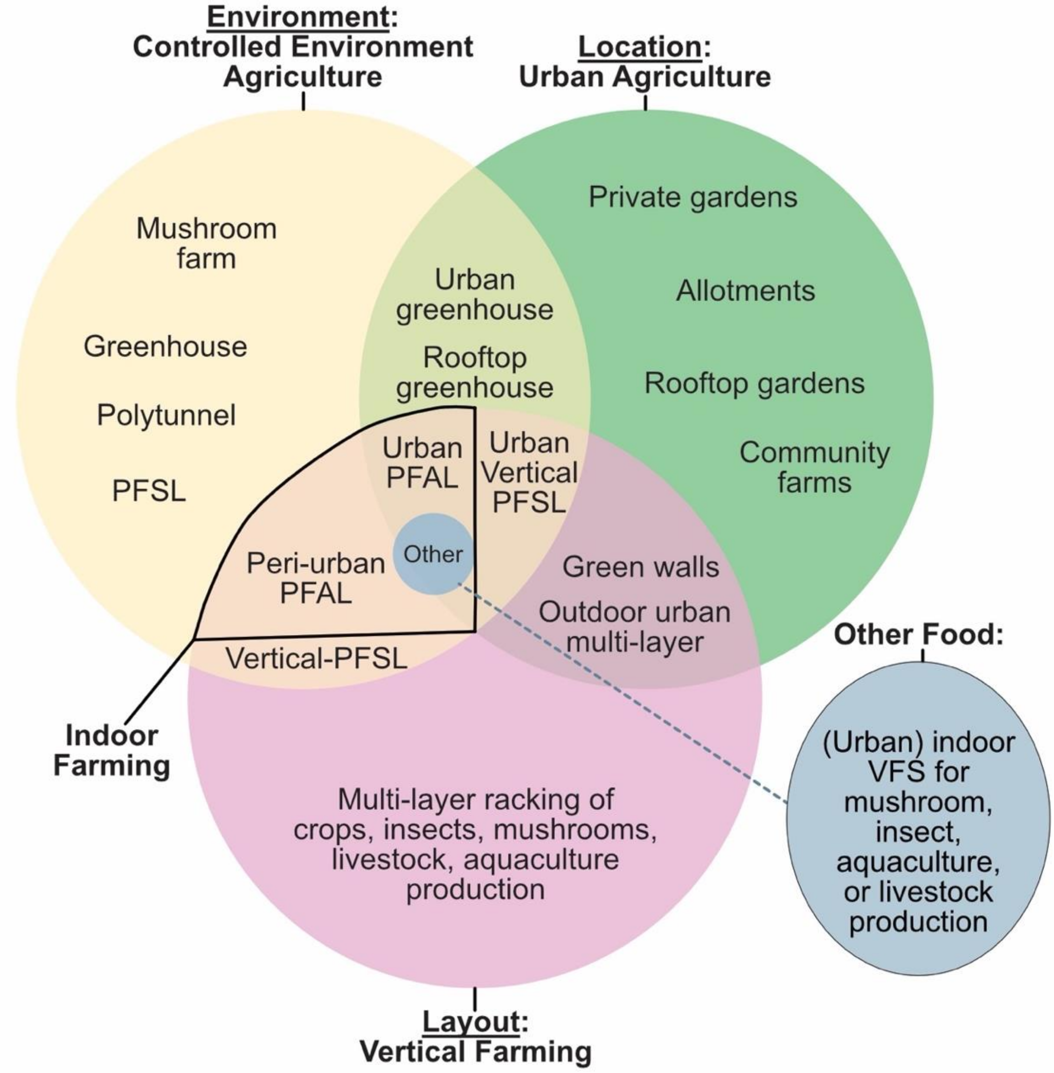


Figure 2.3. Classification of agriculture concepts: vertical farming, urban agriculture, plant factory, indoor farming, and controlled environment agriculture.

2.4 Vertical Plant Farming Configurations

There are many decisions to be made around building types, equipment layouts, configurations, and technologies for developing vertical farms. In this section, the following key design factors for VPF developments are categorised and described: (i) farm placement types, (ii) building integration types, (iii) hydroponic cultivation techniques, (iv) equipment layout, (v) lighting systems, (vi) technology systems and (vii) automation categories. These will then be collated within a configuration typology.

2.4.1 Farm Placement and Building Integration Types

Farms to date can be clustered into five types of placements with respect to buildings, as shown in Figure 2.4.

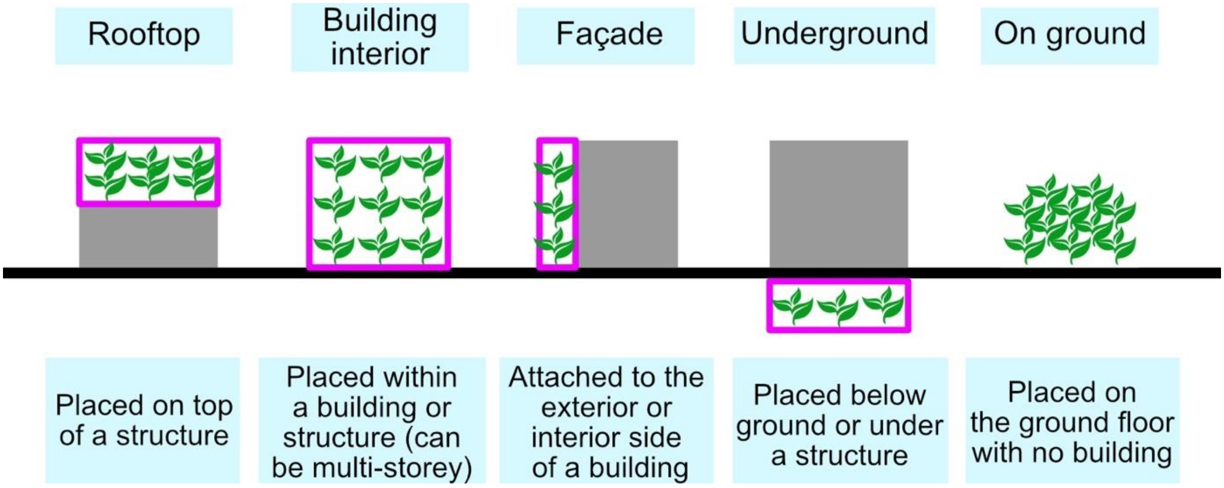


Figure 2.4. Farm placement types. Adapted from Association for Vertical Farming (2019) [126].

Farms can be grouped into three building integration types, as shown in Figure 2.5.

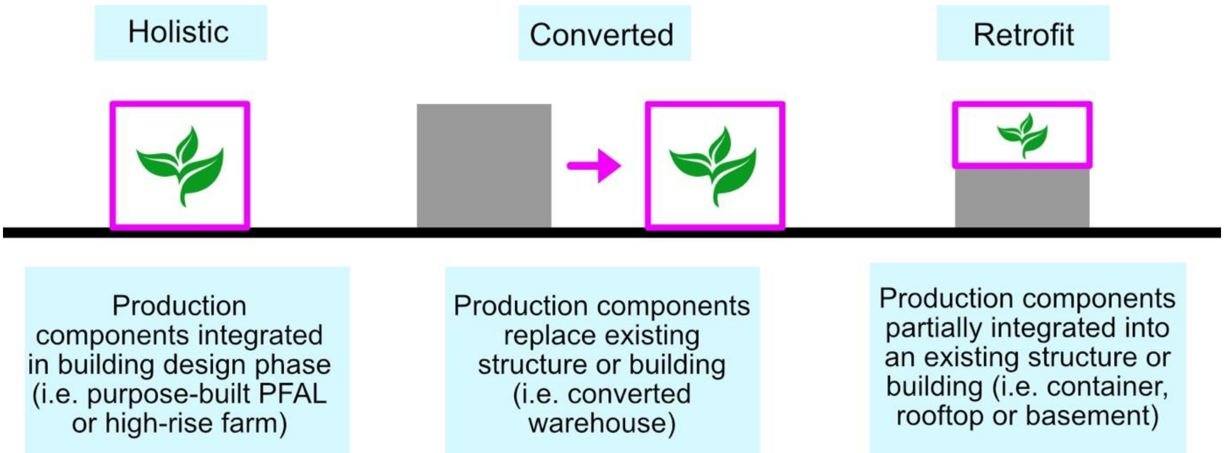


Figure 2.5. Farm integration types. Adapted from Association for Vertical Farming (2019) [126].

2.4.2 Soilless Cultivation Techniques

Soilless cultivation techniques, called hydroponics, are mostly used in VPF. There are a variety of hydroponic techniques. Systems use different methods to achieve particular strengths and weaknesses affecting crop type, growth rate, system weight, and economics. These are illustrated in Figure 2.6 and described in Table 2.3. Strengths and weaknesses can be investigated through the corresponding references in Table 2.3. There are a few exceptions where VPF use soil as their chosen substrate; however, soil is seldom used because of the increased risk of contamination.

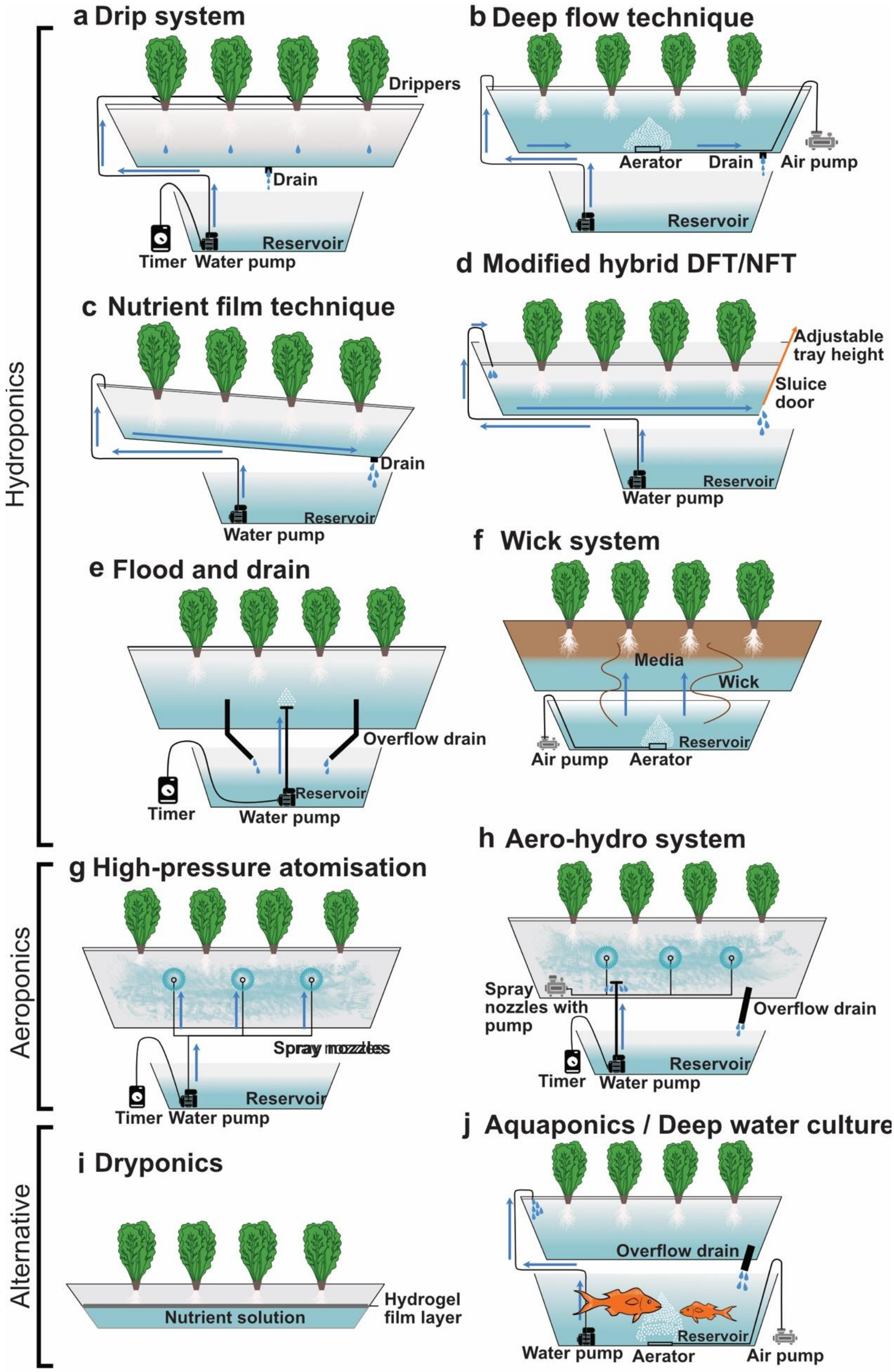


Figure 2.6. Schematics of hydroponic, aeroponic, and alternative soilless cultivation systems, **a-j, are** described in Table 2.3**.** Inspired by van Delden et al. (2022), and Lu & Shimamura (2018) [19,127].

Table 2.3. Hydroponic cultivation methods.

	Technique	Description	Reference
Hydroponics	Drip irrigation (Fig. 2.4 a)	Plants are grown in substrate-filled pots, which are fertigated using a dripper per pot	[127]
	Deep flow technique (DFT) (Fig. 2.4 b)	Plant roots are immersed in a deep nutrient solution which is constantly circulated to ensure oxygenation	[127]
	Nutrient Film Technique (NFT) (Fig. 2.4 c)	a shallow film (2-3 mm) of nutrient solution flows over plant roots down a sloped cultivation bed (slope ratio of 1:70 to 1:100) with upper roots exposed to oxygen	[127]
	Modified DFT/NFT hybrid (Fig. 2.4 d)	In a modified hybrid NFT/DFT system, plants are grown on a flexible cultivation bed that allows adjustable tray and water height, enabling both NFT and DFT depending upon the cultivation objective. It is designed without the requirements for pipes or a bed slope. Panels are supported by frames rather than floating on the water, providing options for more suitable materials than floating foams. When the water depth is shallow (1 cm with an air layer between the panel and the water), the system operates in a NFT configuration. The system operates in a DFT configuration when the water depth is deep (5 cm and no air layer).	[127]
	Ebb and Flow (Fig. 2.4 e)	Plants' roots are immersed in a nutrient solution pumped at timed intervals to the cultivation bed, which is held for a few hours and drained via an overflow. Plants are typically grown on a substrate.	[127]
	Wick system (Fig. 2.4 f)	A thin hydrophilic material transfers nutrient solution from the reservoir to the cultivation bed	[127]
	Deep Water Culture (DWC) (Fig. 2.4 j, without fish)	Plant roots are immersed in a deep tank of recirculated oxygenated nutrient solution. Usually, a panel for supporting plants floats on the solution.	[19]
Aeroponics	High-pressure atomisation (Fig. 2.4 g)	In high-pressure atomisation systems, the nutrient solution is delivered as a fine mist to the plant roots enabling aeration.	[19]
	Fogponics (Fig. 2.4 g)	An advanced form of aeroponics which uses ultrasonic, compressed air, or heating elements to vaporise water into a fog (5–30 μm particles size of nutrient solution)	[128,129]
	Aero-hydro system (Fig. 2.4 h)	Aero-hydro system is a hybrid of aeroponics and hydroponics, where roots are primarily grown in mist, and the root tips are immersed in nutrient solution	[19]
Alternative	Dryponic (Fig. 2.4 i)	In dryponics, plants are grown on a thin hydrogel polymer film which absorbs nutrient solution underneath (6 cm deep) through nano-sized pores which require less water and prevent viruses, fungi, and bacteria.	[130,131]
	Aquaponic (Fig. 2.4 j)	Plants are grown in a hydroponic system combining aquaculture (snails, fish, crayfish or prawns in a symbiotic environment. Nitrifying bacteria break down by-products into nitrates as nutrients for the plants, and water is recirculated back to the aquaculture system.	[19]

2.4.3 Equipment Layout

There are various equipment layouts for vertical cultivation systems, many of which adapt existing systems from horticulture. A summary of approaches has been specified by Beacham et al. (2019) [132] which has been expanded to include vertical grow towers. Figure 2.7 illustrates the equipment layouts possible within a vertical farm.

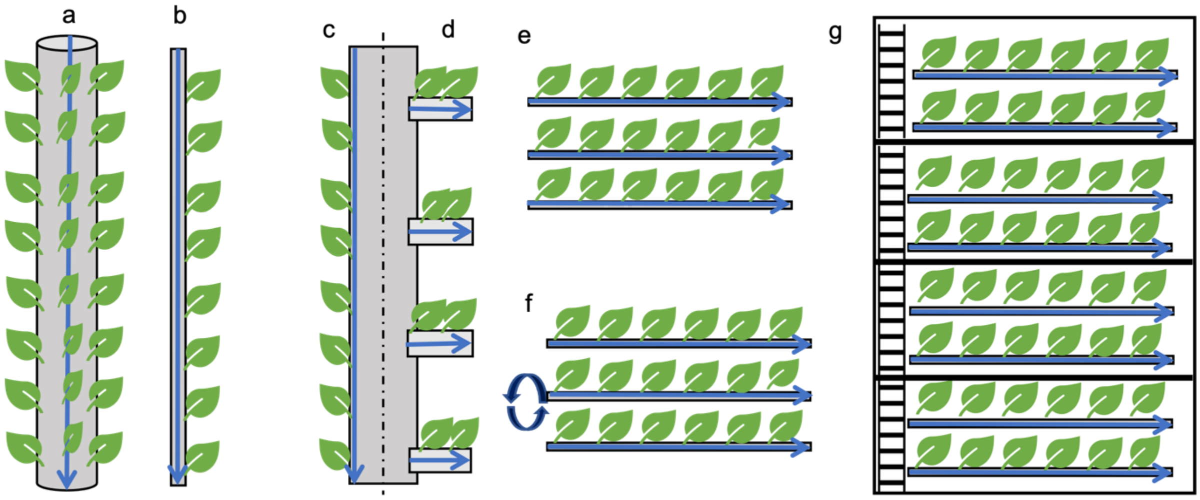


Figure 2.7 Illustrations of VF equipment layouts (a-g). Cylindrical vertical towers where plants grow away from the centre with nutrient solution dripped or misted (**a**). Standard vertical towers where plants are grown outwardly from one side and towers fit within a system rack where nutrient solution is dripped or misted (**b**). Vertical growing surfaces are called 'green walls' where plants are grown on a wall or side of a building for green infrastructure (sometimes called vertical gardening) (**c**). Balconies may be used to grow plants on top of one another (**d**). Vertically stacked horizontal systems where automation or water flow is sometimes used to push plants along the horizontal axis (**e**). Mobile racking systems with rotation incorporated either to move plants along the vertical axis for solar light or to move racks along the horizontal axis to maximise floor space (**f**). Multi-storey towers or racks that require stairs or an elevator to access all the growing racks, which are sometimes in their own enclosed space with different climates and crops (**g**). Inspired by Beacham et al. (2019) [132]**.**

2.4.4 Lighting Systems

For vertical plant farms, choosing the appropriate lighting is essential. VPF energy use is mainly dictated by the requirement to provide photosynthetically active radiation (PAR) for plants to activate photosynthesis and stimulate growth [19]. The various lighting options are as follows:

- High-pressure sodium lights – previously, these were the most commonly used among commercial indoor growers before other options were available [3].
- Fluorescent grow lights – there are two types, fluorescent tubes and compact fluorescent lights. Fluorescent lights overtook high-pressure sodium lights as the

most common in indoor farming. They are substantially more affordable compared to other options. [3]

- Lighting-emitting diode (LED) lighting systems – the advancements in energy efficiency and spectrum of LEDs have unlocked the affordability for VPF operation since 2005 [3]. LEDs are now the most common lights for VPF due to their superior energy efficiency and low waste heat [3].

The efficiencies of LED lighting systems continue to improve substantially year by year, with forecasts that every decade the cost per lumen will fall by a factor of 10, and the amount of light generated will increase by a factor of 20 [133]. This is called Haitz' Law [133]. The cost of LED lights is drastically higher than the other two types, but the spectrum can be adjusted and tailored to the crop requirements. These tailored 'light recipes' is an emerging area of research investigating the influences on yields, plant shape, photosynthetic efficiency, nutrients and flavour profiles [72,134]. There are three approaches: broad-spectrum (white light), narrow-spectrum, and flexible spectrum.

- Broad spectrum lights emit photons from the entire PAR spectrum range [134].
- Narrow-spectrum lights emit the precise spectrum for a specific crop and its growth stage.
- The most expensive option is adjustable spectrum lights which provide flexibility for various crops and their growth stages.

There are many variations of LED lighting systems for different strengths, spectrums, and combinations of the two. However, there is a lack of detailed information on lighting conditions required for the optimal growth of plant species [135]. Due to this paucity of information, Fujiwara (2022) has authored a book chapter on LED product terminology and performance that allows comparison [136]. In addition, in 2015, the American Society of Agricultural and Biological Engineers released a standard for methods for measuring and testing LED lighting for plant growth [137].

2.4.5 Technology

VPF is essentially the integration of technologies to emulate nature, spanning from machine learning algorithms to renewable energy power plants. In Figure 2.8 both hardware and software technologies involved in VPF are summarised. Most of these technologies are intertwined and have yet to reach full maturity for optimal plant growth and production. In a review, Kalantari et al. (2017) examine the literature on VPF technology and highlights the technical aspects that must be advanced to improve operability [92]. This section will briefly discuss the technologies of robotics, automation, sensors, and renewable energy. Detailed descriptions of heating, ventilation and air-cooling (HVAC) in VPF can be found elsewhere due to the complexity of specifying an adequate system that considers heat gain/loss induced by crops [138,139].

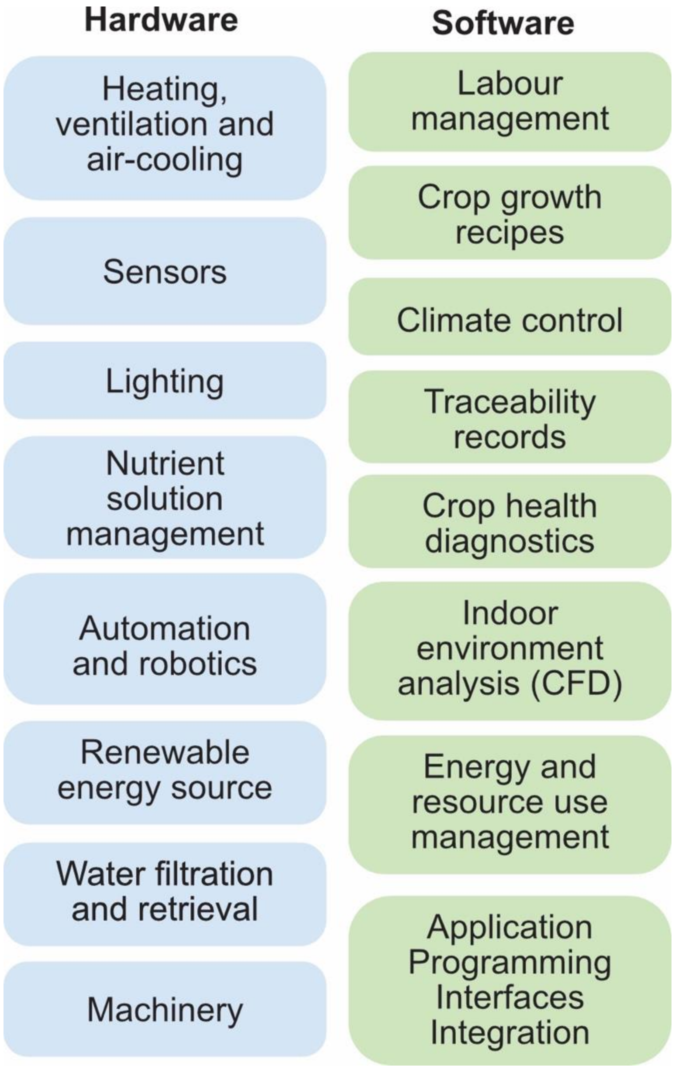


Figure 2.8. The technologies associated with VPF.

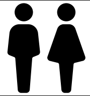
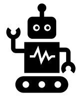
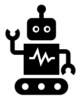
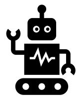
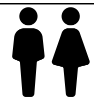
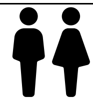
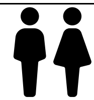
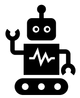
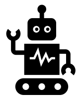
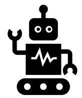
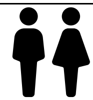
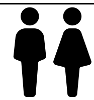
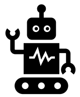
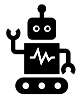
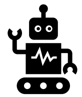
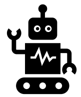
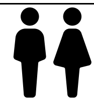
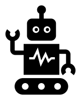
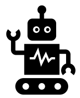
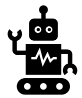
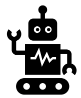
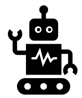
In the pursuit of mass-market profitability, farms have begun automating repetitive tasks, such as harvesting or propagation, up to 24 hours a day in any growing conditions. The main opportunities involve automating parts of the growing chain that are repetitive and risk-prone. An automation classification system was developed by a VPF technology company, OnePointOne, to define and distinguish the levels of automation capability for vertical farming (see Table 2.4) [140]. The majority of commercial VPF operations have automated basic growth, some operate commercially using conveyor automation [141] and the most well-capitalised farms have attempted to progress to adaptive automation using artificial intelligence techniques where the system adaptively responds to plant needs [142,143]. However, it is unclear to what extent adaptive automation has been achieved in the industry. System and full automation have not yet been achieved. Other VPF automated systems make use of advancements in logistics automation technologies, such as the pallet-and-lift method [144] and programmable robotic arms for moving and placing plants [145].

Connecting web-enabled sensors and data management to data analysis algorithms have enabled VPF to maximise productivity. These technologies can be powered by machine learning techniques to process millions of data points into actionable insights such as optimal growing conditions called crop growing recipes or pest and disease identification. In addition, many sensors are used to measure and record environmental, atmospheric, and plant-specific parameters and resource use. Many commercial systems also have application programming interfaces which enable system integration amongst sensors, cultivation management platforms, and systems. Software that enables this has been reviewed by [146,147].

The issue of energy consumption of VPF has been a critical priority in recent years, with one of the most resounding criticism being the associated environmental impact, especially targeting greenhouse gas emissions [89,148]. Sourcing renewable energy for VPF has become paramount, even better if it can be produced on-site or in synergy with a power plant to reduce reliance on the electrical grid. Some PFALs have implemented on-site photovoltaic panels [149], geothermal [150], and hydrogen fuel cells [87] to supplement their energy use from the grid. However, land requirements for energy production are much higher than the cultivation area with substantial conversion losses. With natural energy and electrical battery advancements, a vision of energy autonomous-PFALs becomes closer to reality. The strategies for improving energy efficiency and reducing greenhouse gas emissions are explored by several researchers [87–89]. Meanwhile, novel research begins to address the use of waste heat for vertical farms from power plants, treatment of wastewater, anaerobic digestion, rainwater capture and synergising with other food sources such as aquaculture or fungiculture [151].

Moving towards the next evolution of VPF, machine learning, indoor VPF crop breeds, renewable energy sources, and higher energy efficiency technologies will play a critical role. It is expected that such advancements will benefit the economic and environmental sustainability of VPF.

Table 2.4. Automation classification for the vertical farming industry (adapted from OnePointOne [140])

Automation capability	Definition	Core cultivation	Pre- and Post-Growth	Logistics and Inspection	Maintenance and Servicing	Market Intelligence
No automation	All processes within the vertical farm are managed by human decision-making and labour.					
Basic growth automation	All subsystems that relate directly to plant life support (light turning on/off, nutrient pH control, air temperature and humidity control) can maintain cycles and set points without human input.					
Conveyor automation	Some or all start and end phases of the plant's life cycle (seeding, germinating, harvesting and packaging) are automated using non-intelligent machines, much like traditional manufacturing.					
Adaptive automation	Humans have no physical interaction with plants, which are moved, fed, monitored and inspected by machines and computers able to adaptively respond to plant needs. Humans must service machines.					
System automation	Humans are only responsible for defining the outputs of the self-sufficient system; all farm operations are automated, including required input refills, servicing and maintenance operations.					
Full automation	The only humans involved are customers; the farm responds automatically to the market's demand and coordinates logistics and delivery without human decision-making and labour.					

2.4.6 TYPOLOGY OF CONFIGURATIONS

A typology of VPF configurations can be developed by combining and adapting the scattered classifications from the Association of Vertical Farming's classifications of UA [126], Bertram's automation classification [140], the VF key factors detailed by Kozai [16], and a summary of VF layout approaches by Beacham et al. [132]. Figure 2.9 is an illustration of the proposed typology. It can be adapted for CEA and non-horticultural VF by changing the emphasis of farm classification and product type.

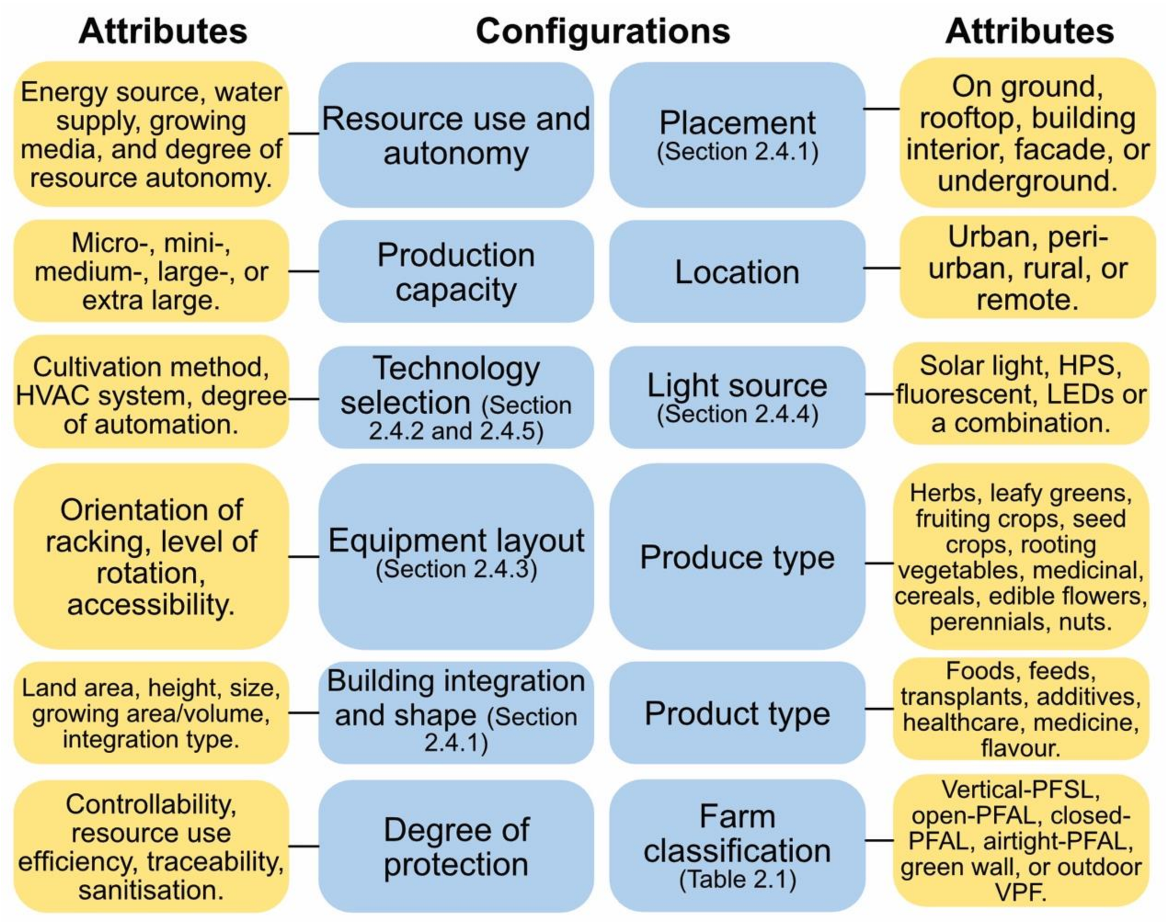


Figure 2.9. Typology of VPF by configurations and attributes (cf. Kozai (2022) [16])

The typology is an important starting point to stimulate further R&D and enable collaboration of data sharing. Businesses dedicate substantial resources to R&D, partially due to a lack of standards and available crop growth recipes, hindering the financial viability of commercial projects. A typology can help inform this. Moreover, the economic analyses in the literature are disparate [75], and alignment with a typology will enable more transparent and replicable results.

Risks associated with VF are an underexplored area of research. To correctly identify and evaluate risks, risks must be clustered according to the classification and configuration of farms. Farm operators report that each vertical farm is unique in its building, business model, and system selection [69]. For this reason, a comprehensive understanding of the types of farms will benefit any risk assessment conducted.

2.5 Vertical Plant Farming Business Models

Companies across the world have been innovating business models. VF has a profound capacity to disrupt traditional modes of distribution, allowing vertical integration of the supply chain. Commercial VPF projects can be built and developed in previously inaccessible locations constrained by the environment, arable soil, or space. This can reduce supply-chain risk, inconsistent product, and food miles. Three distribution models determine the location of a VF project identified by Baumont de Oliveira and Dyer [69] which are represented in Figure 2.10.

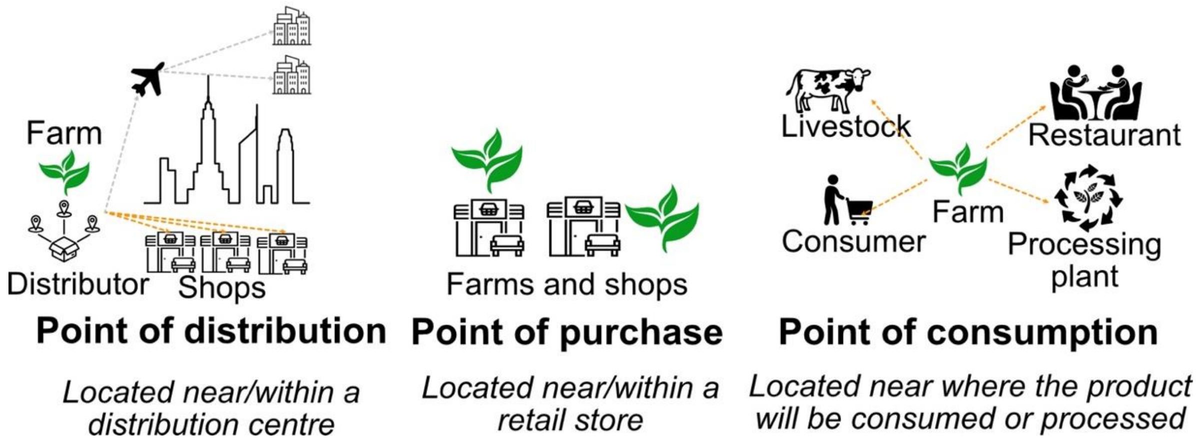


Figure 2.10. Distribution models (cf. [69])

Several researchers have discussed the types of business models to date. Al-Kodmany (2018) reviews many case studies of both operational and proposed developments [38], identifying the emerging concept of hybridisation of profit-driven commercial operations and non-profit morals and ethics within a single operation [38]. In the second edition multi-authored book, “Plant Factory”, there are several chapters examining exemplar case studies and their business models across different countries [31,110,125,152]. It is clear that alongside commercial growing, many VF operators also focus on direct sales of systems, software development, and R&D. In Table 2.5, a categorisation of the commercial business models and their trade-offs with example farms are provided.

Table 2.5. Business model categorisation and associated trade-offs.

Business Model	Suited Crops	Strengths	Weaknesses	Farms
Retail: high value - low volume	Microgreens and herbs.	High-value crops and customers are suited to vertical farming placed near point-of-consumption.	Difficult to scale (niche market), labour intensive, affluent urban areas primarily targeted, and higher demands of customer service required.	[34,153]
Wholesale: high volume - medium value	Leafy greens, salads and herbs.	Economies of scale, able to incorporate automation, improved shelf life and attractive to investors. Placed near point-of-distribution.	Expensive set-up costs, at risk of producing a commodity crop and expensive rent or property costs if in an urban area.	[149,154, 155]
Larger crops: high value – low volume	Fruiting crops and berries	Higher value crops nutritionally and financially. Vine crops naturally grow vertically.	Requires more investment for R&D. High energy demands. Already grown well in greenhouses.	[156,157]
Speciality crops	Rare herbs, and edible flowers.	Premium value crops. Able to grow rare and heirloom plants that are difficult to source.	Affluent or wealthy markets only, crops can be spoiled easily, and the market cap is small.	[158–160]
Plant breeding (R&D)	Any	Rapid crop generations can create specialist growing environments, and breed for specific characteristics.	Need to know growing conditions (outdoors/indoors) to ensure the seed performs well in the environment. Long R&D cycle to bring a seed to market.	[64,161,162]
Specific parts of the lifecycle	Trees, floriculture, and seedlings	Can specialise in parts of the growing cycle for accelerated growth through consistent conditions.	Crop selection is narrower and does not take a plant from seed to harvest.	[163,164]
Medicinal/ Plantceuticals	Cannabis, healthcare and cosmetic ingredients.	High-value crops. Total control allows consistent plants and high biosecurity levels suited to the pharmaceutical industry. It can be placed at point-of-processing.	Potentially closed industry (highly regulated contracts) and primarily available to the wealthy market.	[165,166]
Hybrid social enterprise	Any	Social, educational, and welfare aspects of providing fresh food in urban communities.	A complex business model with multiple facets to manage. Management of two business objectives.	[167–169]
Guaranteed customers	Fodder, leafy greens and salads.	Consistent demand (such as livestock or people in remote locations) and the system can grow crop selection all year round. Low waste rates.	It can be challenging to provide resource inputs depending on location. If not controlled remotely, then on-site staff will require training. Creates dependence on the system.	[170–172]
Farming-as-a-service (retailer owns/loans the system)	Leafy greens, salads and herbs	Modular systems can be placed at point-of-purchase, which improves the retail experience for consumers, builds brand awareness, and reduces distribution costs.	VF company usually takes care of the farm, including installation, cultivation, harvesting, and maintenance. Any mistakes are publicly visible. Requires a mobile team to service systems.	[150,173, 174]

Over the past five years, the industry has become primarily segmented across three different models: wholesale, retail, and farming-as-a-service. In addition, there are a growing number of farms serving specific niches such as microgreens, animal fodder, plantceuticals, or speciality crops [42]; however, these farms are less publicly visible, and it is challenging to assess their scale.

Retail: high value - low volume

There are numerous small retail-focused farms and probably more than any other business model. This is because low-volume farms are less capital-intensive, requiring less equipment and real estate.

Wholesale: high volume - medium value

The number of large PFALs serving wholesale markets. The capital required to develop and operate such farms is high. Some of these farms use conveyor automation, for example, Plenty [155] and Planet Farms [175]. One example, 808 Factory, has two profitable PFALs in Japan selling lettuce to supermarkets, of which they have shared detailed information about their set-up [125,143]. One of the main limiting factors for scaling has been the size of the market willing to pay a premium for quality produce.

Farming-as-a-service (retailer owns/loans the system)

Farming-as-a-service companies have demonstrated product-market fit with various sizes, rapid expansion, and customisable modularity. Some companies, such as PlantX in Japan, lease or sell a large-scale PFAL to a retailer, which the VF company manage and operate [173]. Meanwhile, InFarm, based in over 12 countries, operate over 1400 of mini-PFALs within retail stores and modularised PFALs to supply them [174]. Butturini and Marcelis (2019) provide more examples of in-store farms [110].

Emerging models

The other emerging business models require a longer development cycle but are gaining traction in commercial viability. For example, PFAL-specific tipburn-resistant lettuce has been bred by a start-up, LeafLab, in Japan [64] and luxury Japanese strawberries are grown and sold by Oishi's PFAL in the USA. The use of mini-PFALs also has many purposes, and Lu et al. (2022) explore the associated business models in depth [117].

There are likely many companies profiting from PFALs for medicinal use plants; however, due to the closed nature of this industry, it is difficult to estimate the model's prevalence. In particular, Cannabis has been reported to grow well within vertical farming systems [165]; however, short-statured varieties or younger plants are more suitable [3]. Climate control and light uniformity can prove particularly complex for Cannabis [176]. Most countries are witnessing an upward trend in Cannabis cultivation (especially indoors) and popularity between 2010-2020 [177]. It is likely to be economically lucrative but further research is required. VPF may play a significant role in the production of plant-made pharmaceuticals in the coming years.

2.6 ECONOMIC ANALYSES REVIEW

In this section, the economic analyses of VPF are examined. It has been noted by academic researchers and industry practitioners that there is a scarcity of peer-reviewed research investigating the economics underlying the construction and operation of VF [74,178,179].

2.6.1 STATE OF KNOWLEDGE ON VPF ECONOMICS

Capital inflows into the VPF sector have been significant, with more than USD $2.6 billion invested since 2016 [81]. In some cases of companies receiving enormous investment rounds, insiders complain that it is mostly "smoke and mirrors" [72,180], indicating that a path to profitability may not be so clear cut. High capital and energy costs fuel scepticism regarding the economic viability of VPF projects [181] with critics claiming that VPF economics is not grounded in reality [40,43]. Colangelo (2022) identified financial valuations 300-1000 times the revenue of the most heavily financed VPF companies [182], highlighting the inflated investment valuations. Other complaints include high energy conversion losses and urban real estate prices [115]. The Japanese PFALs are one, if not the only, VPF model of profitability that has been fully implemented with an almost complete dataset available [82,86].

The literature on the economics of vertical farming is particularly scarce when compared to other disciplines within the field, with almost all articles stating the need for further in-depth analyses [36,76,82], making it challenging to address the associated criticisms accurately. Detailed financial analyses of capital expenditure (CapEx), operational expenditure (OpEx) and revenues have been hard to produce due to the complex nature of combining architecture, agriculture and new digital technologies with an urban food-water-energy nexus context [76]. Calculations tend to be for a particular scenario and are difficult to generalise [76], especially as technology evolves quickly. The lack of financial or production data that is publicly available is to be expected in any emerging industry, as profitability data is a competitive edge guarded as proprietary data. System vendors continue to sell and distribute their systems across the world [183–186] whilst some explicitly state profitable system economics [187–189]; the literature is yet to verify or reflect this. Anecdotal experiences seem to claim the opposite [69].

Economic viability remains one of the primary challenges for realising VPF projects [76] Researchers profess that the most significant barrier to the realisation of VPF is not the capability of the technology but the uncertainty of economic feasibility [190]. Therefore, exploring the reality of VPF economics with real and tested data is needed to demystify the sector to help entrepreneurs and investors identify strategies for profitability [191].

In September 2022, a search in Elsevier's Scopus database for "economic" and "vertical farm" or "plant factory", including slight variations, revealed 35 research articles that discuss VPF that address considerations of the economics. Further investigation within the aforementioned literature and industry whitepapers reveals 7 additional items. The 42 analyses are a mixture of 31 scholarly articles, 3 book chapters, 5 industry reports, 2 vendor calculators, and 1 commercially available economic estimation software. In Table 2.6, the relevant economic analyses are classified according to Table 2.1 and Table 2.2, and described alongside their associated results. If the analyses omitted information about the farm in question, such as the degree of insulation or airtightness, the farms were classified as semi-closed-PFAL. No mention of HVAC or CO_2 injection would be classified as an open-PFAL. When multiple PFALs of different types are aggregated, the term "mixed" PFALs is used.

Table 2.6. Available VF economic analyses alongside a description of the study.

Type	Source	Farm classification	Remarks
Cost analyses	[36]	Hypothetical 37-storey 2500 m^2 vertical hybrid farm	An economic simulation in Berlin, Germany. The building would require a $200 million investment. The cost of production is presented in probability distributions, although it is unclear how the distributions are calculated. Costs are €3.5–4 per kg in 44% of cases.
	[90]	Hypothetical 50 m^2 semi-closed-PFAL	A simulation of life cycle costing. Sensitivity analysis results indicate added value crops such as herbs and pharmaceutical ingredients are necessary for economic viability.
	[86]	Hypothetical 1000 m^2 closed-PFAL	A business planning spreadsheet developed based on experts' and industry practitioners' experience. Most comprehensive data set in the literature. Cashflow projections for a profitable farm with a 7.8 payback period.
	[192]	Hypothetical 5000 m^2 open-PFAL	A feasibility study using central limit theorem to assess ROI in Wuhan, China. The breakeven on investment in this PFAL analysis is 11.5 years. Unviable crops are selected.
	[193]	Hypothetical 465 m^2 semi-closed-PFAL	A cost analysis compares the economic viability of a PFAL in São Paulo, Brazil, to Denver, North America, using vendor's data. São Paulo provides a cheaper scenario, but low costs cannot compete with field-based farming product prices. Predicts USA has a 14.2% IRR compared to −19.1% in Brazil.
	[103]	Hypothetical 6-storey 200 m^2 semi-closed-PFAL	An analysis of the economics in Delhi, India. The payback period is calculated to be 64 years. Unfeasible and unviable crops are selected. There are severe errors described later in the discourse.
	[82]	Hypothetical Japanese closed-PFAL data [86] and substituted with modern data	An analysis tests various scenarios (changes to scale, operations and market context). Results show a significant decline in capital costs, especially equipment (45%), substantially increasing profitability (ROI rose from 1.8% to 14.3%). The scale of operation is critical to profit and depends on the proportion of fixed costs. Doubling the size of the PFAL enhances the ROI from 14.3% to 22%.
	[117]	2 walk-in type mini-PFALs and 1 open mini-PFAL	An analysis of the cost performance in cities in Japan and China. All three business models and mini-PFALs can be economically viable but is primarily dependent on crop price. The required crop price for break-even ranges from USD $12-75 depending on the business model, system and location.
	[194]	Compilation of data from 26 mixed PFALs (hypothetical and built) across five different countries.	An analysis of the economies of scale of PFAL construction costs and their impact on economic viability. The study concludes that a 30% yield or crop price decline would easily bring PFAL bankruptcy. On the other hand, the unit construction cost declines by as much as 55%, to a level of less than half, when the scale of PFALs increases by 10,000%. The optimum scale of PFALs not only depends on the scale but sustaining and increasing the number of buyers. The minimum scale, which ensures the breakeven in crop production in PFALs, is estimated to be less than 40 m^2 for lettuce and more than 100,000 m^2 for strawberries.
Software and	[76,195]	Hypothetical user-specified PFAL/PFSL	A flexible system for predicting costs and ROI with results shown for several scenarios with sensitivity analysis. ROI is sensitive to electricity price, crop price and CO_2. Software not publicly available.

decision support systems	[75]	1 real semi-closed 220 m^2 PFAL case and hypothetical 1000 m^2 closed PFAL [86]	A flexible risk analysis tool develops on the framework of [76]. The study utilises imprecise probabilities and survival modelling techniques to evaluate the quasi-insolvency of two PFALs. In the absence of concrete data, they use imprecise estimations for uncertain variables and risks to show the best-, worst-, and most likely case.
	[84]	Hypothetical user-specified PFAL/PFSL	A commercial and flexible digital platform for economic estimation of UA projects. CapEx, OpEx, and yield estimates alongside 15-year projection. Not peer-reviewed or validated.
	[196]	Hypothetical 500 m^2 closed-PFAL	A decision support framework to optimise NPV for UA. Field-based crop data is used. Results show that leafy greens are economically viable, and PFALs are the most profitable farm. Software is unavailable.
Greenhouse and VPF comparison	[85]	Hypothetical 279 m^2 semi-closed-PFAL and a 1171 m^2 greenhouse.	A simulation of a hypothetical scenario comparing the profitability of growing lettuce in Quebec City, Canada. Results show that the costs to equip and run the two facilities are similar, with higher gross profit for PFAL. The conclusion is invalid due to improper assumptions explored later.
	[91]	Hypothetical 225 m^2 closed-PFAL and a 1674 m^2 greenhouse	A simulation of scenarios to compare a PFAL and greenhouse under various financing schemes in Denmark. Results show that regardless of the financing scheme, the PFAL facility was much more profitable than the greenhouse, with high IRR rates and a payback period between 2–6 years. The conclusion is invalid due to improper assumptions explored later.
	[197]	Hypothetical 518 m^2 greenhouse, PFSL and PFAL single-tier.	A comparative economic analysis for energy saving technology greenhouse, PFSL and PFAL for growing strawberries on a single-tier. All plant factories showed an investment payback period of seven to nine years, comparable to typical greenhouses.
	[198]	Hypothetical 1028 m^2 greenhouse and closed-PFAL	A comparison of costs in Ohio, USA. The cost difference between the greenhouse and the PFAL was comparable (an average of US $ 0.12 per head difference with almost no difference in winter).
Other	[199]	Hypothetical 10,000 m^2 semi-closed-PFAL	An analysis of the production and finances of growing wheat. The simulation concludes that the PFAL could produce up to 1,940 ± 230 t/ha/year, approximately 600 times the current average yield in a field. It is unlikely wheat will be economically competitive soon, but it could play a role in the future.
Industry surveys and reports	[62]	56 real mixed PFALs	The results of a self-reported survey (USA based). Aggregated data for OpEx and profitable crops.
	[115]	215 real mixed PFALs	The aggregated results of Japanese PFALs with production costs and percentage of profitable farms.
	[42]	190 real mixed PFALs	Aggregated and self-reported data on profitability and revenue from around the world.
	[102]	Hypothetical 5-storey vertical hybrid farm	Cost performance of next-generation VF concept. The design concept is broken down into estimated CapEx and OpEx. The concept is not economically viable due to high start-up costs, real estate, electricity consumption, and labour, which pose challenges.
Vendor tools	[120,188]	Hypothetical 28 m^2 open-PFAL (container)	A business planning spreadsheet to estimate economics by a vendor for their container farm. Computes capital costs, expected yield, cash flow statements and payback period. According to anecdotal reports, hidden factors are not accounted for [69,200].

These analyses discuss the economics of VPF from a range of perspectives to compute CapEx, OpEx, productivity, and profitability, primarily for hypothetical scenarios. However, many analysts struggle to provide a balanced assessment of the feasibility of projects and are disparate due to varying farm characteristics, business models and different metrics used without quality data.

Some analyses compare greenhouses vs semi-closed-PFALs [85,91] but paint PFALs in a favourable yet perhaps unrealistic light, which will be explained later in this review. Customisable analyses also exist for scenario planning [76,84,146] which aim to help entrepreneurs compare different systems, buildings and business models, but only one is available for commercial use [84]. Only four analyses [62,84,115,194] are based on real-life working farms but have some pitfalls, such as sample selection, aggregation across farm types, and self-reported data, making them hard to compare.

Several economic analyses examine high-rise VPF [36,102,103] yet all are hypothetical designs. Despite serious proposals, technological and economic limitations have prohibited the realisation of such projects. The success and maturation of PFALs will likely determine the feasibility of high-rise multi-storey developments. Therefore, looking at existing PFAL economics would accelerate developments. Without this, published studies such as Sarkar & Majumder (2019) estimate a six-storey VF in India growing 43,000 kg of a variety of unsuitable crops (i.e. potatoes and peppers), as "highly profitable" with a 64-year payback period, yield projections from greenhouse data in 1986 and annual operating costs of USD $6618 [103]. This analysis is deeply flawed. [36] and [102] conduct much more sensible analyses estimating sky-high costs but emphatically admitting that the industry still has a way to go before high-rise VPF makes sense.

2.6.2 Capital Expenditures

Only a small number of the analyses address the capital expenditure (CapEx) involved in VPF, and fewer still are comprehensive in their examination. In supplementary materials, Table S1 collates the information gathered from the analyses (labelled A to E) that provide a breakdown of CapEx of various farm scenarios. The values from the studies have all been converted into metric units, classified according to Table 2.1 and Table 2.2, and currency converted to British pound sterling for comparability. Some analyses were omitted due to unrealistic estimations, such as £187,000 for a six-storey VF growing fruits and potatoes [103] or operating costs below £560 for 5000 m^2 VF

[192]. The misinformation in such analyses is common, highlighting the lack of valid data. More customisable analyses [76,84,146] have also been excluded due to their dependence on user inputs.

Each farm is unique, and there is no one-size-fits-all; however, some general trends can be identified. CapEx ranges from £174-1243 per square metre and is a function of height (no. of tiers or storeys) and sophistication (environmental control, automation and growing systems). More storeys or levels and higher output mainly result in higher CapEx, which is expected, mostly from the higher number of lights required. The exception is the container farm model (analysis E), which has the highest comparative CapEx, £35.9/kg/year, after the skyscraper mixed vertical farm (analysis D) of £49.1/kg/year. Without selling the product at an extremely high price to the market, the container will not provide a viable financial ROI. From the analyses, the CapEx is typically driven by three elements shown in Figure 2.11.

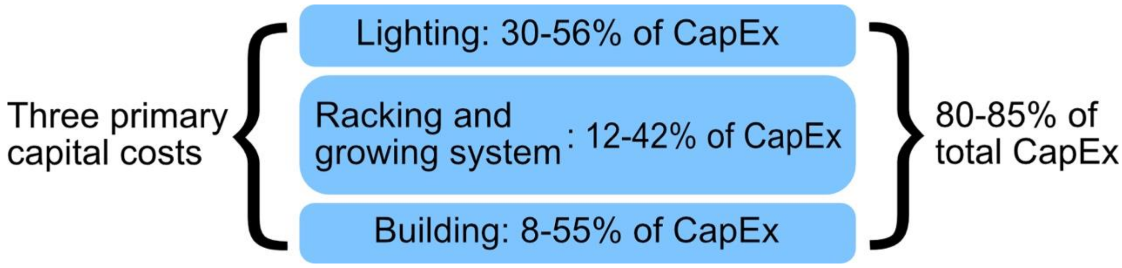


Figure 2.11. CapEx components for PFALs

Only one analysis, which examines a small PFAL of 50 m^2 (analysis A), sufficiently examines building costs and budgets for adequate climate control and contingencies [90]. [90] provides a comprehensive analysis that uses lifecycle costing and scenario analysis, providing a range of CapEx per unit area. The Denmark study (analysis C) and Quebec study (analysis B) both evaluate semi-closed and closed-PFALs as profitable [85,91] but appear to underestimate HVAC (0.88 and 0.8%, respectively). The Denmark study analyses a closed-PFAL, which implies the farm internally manages the microclimates for the dense basil will be essential to achieve high yield, and the HVAC cost would likely be more than the suggested £1985. HVAC systems are complex to configure and calculate without an expert considering the entire building. Depending on the level of control required and the insulation of the farm, this value could go up to 15% [84]. Similarly, both greenhouse vs PFAL studies adopt a leasing strategy to avoid considering construction or refurbishment costs, but if the farm is wholly insulated from the external climate as assumed by [91], then building refurbishing will be crucial.

Several types of CapEx are missing from most analyses, for example, propagation systems, processing, cold storage and building costs. These are minor expenses and may justify their omission. However, real estate costs are frequently avoided too, perhaps because they depend completely on location and building [84,146]. In 2022, Zhuang et al. conducted the first assessment of the economies of scale of PFALs, agreeing that the construction cost data of PFALs is scarce [194]. [194] compiles data for 26 PFALs from a combination of the studies mentioned earlier, practical experience, hypothetical designs, and constructed buildings for their assessment, using an auxiliary dataset (14 PFALs) with missing data to strengthen their conclusions.

2.6.3 Operational Expenditures

Information on OpEx comes in various forms across the analyses, and not all the studies that detailed CapEx highlight OpEx, and vice versa. This makes the correlation challenging to compute. Typical OpEx breakdowns in percentages and costs are presented for diverse VPF types in Table S2 of supplementary materials. Again, records have been standardised in metric units and British sterling pounds.

The production costs consist of three major components that account for roughly 75-80% of OpEx in most cases [63] and are illustrated in Figure 2.12 alongside suggested values for supplies and maintenance from [93].

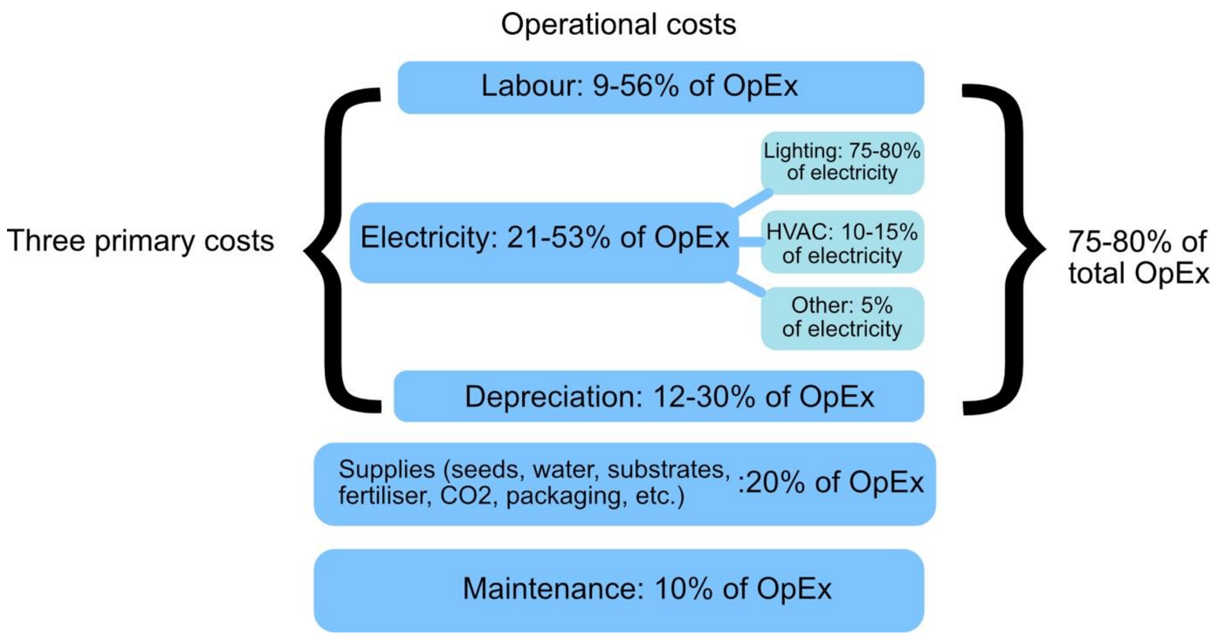


Figure 2.12. OpEx components for PFALs (cf [93,201]).

Depreciation is not accounted for in many analyses. Another trend is that labour covers wages per hour rather than annual salaries for management; however, many PFALs have management teams. There are a few exceptions [91]; labour is grossly underestimated in many analyses, especially when you compare the percentage costs to the industry report of self-reported farm statistics for labour (56% of OpEx) [62]. An informative analysis does not need to contain every OpEx, but accounting for energy, labour, depreciation, and supplies is necessary. Rent is frequently omitted, and keeping it relatively low compared to other costs appears common.

2.6.4 Discussion

This discussion explores the characteristics, caveats, comparisons and conclusions of the analyses more deeply.

Profitability

The profitability of commercial VPF has been in question, yet many of the analyses determine their respective PFALs as profitable. The issue is that the majority of the analyses are speculative, and real validated data is not publicly available that demonstrates a proven viable business model. Despite this, three sources present aggregated data regarding the profitability status of commercial VPF operators. Two industry surveys provide self-reported data [61,62], whilst the third is a census conducted in Japan by its government on the largest sample of PFALs. Collectively, the three surveys represent 494 VPF projects (assuming that the Japanese census includes the same farms in 2014 and 2018). Figure 2.13 shows the results of these surveys.

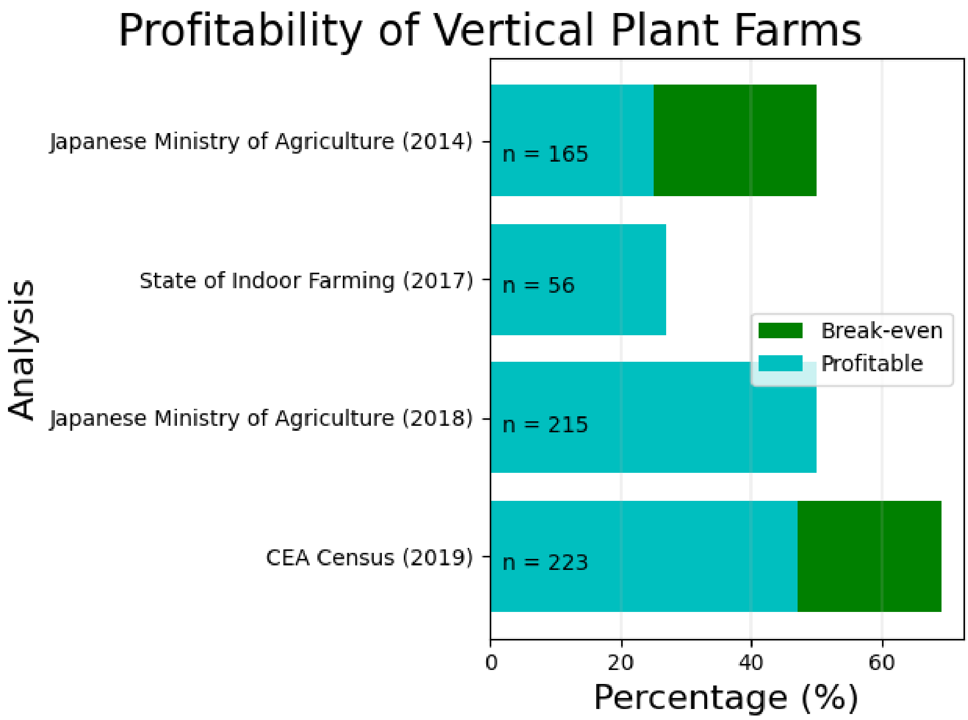


Figure 2.13. Profitability status of VPF projects alongside sample size (n) (cf. [61,62,115])

There were double as many profitable PFALs in Japan in 2018 than 4 years before [115], indicating rapid technological improvement, experience and a maturing market. The State of Indoor Farming Report (2017) [62] highlights that only 27% of indoor vertical farms (which can now be called PFALs according to the new classification) were profitable (mainly in the USA), which was the least profitable type of farm [62], and this number also seems to be increasing quickly as the CEA census (2019) [61] indicates 47% are now profitable and 22% are breaking-even in 2020 [42]. The aggregated sample sets represent different configurations, economies and points in their development cycle, making it impossible to draw fair comparisons. However, the data shows a positive picture of increasing profitability over a short period.

There are two simultaneous paths that Kozai (2018) [201] presents to improve profitability for existing operations:

- A 24% production cost reduction is possible by improving electrical and labour efficiencies by 50% (i.e. smart operation of electrical equipment, automation, training, and farm layout).
- A 50% increase in sales as a result of higher quality, yields and customer focus (i.e. value-adding, packaging, and easily handled crop varieties) [63].

It is expected that electricity and labour costs will be further reduced through improvements in technology and efficient practices [63]. Methods to reduce energy costs by 20-30% and by a theoretical 50-80% are possible by executing steps according to [115]. They claim that several PFALs in Japan have already doubled their cost performance between 2013 and 2017 [63]. If trends continue, such as Haitz's Law [133], increasing demand for local produce [202,203], a better understanding of crop requirements [204] and labour efficiency improvements [205], then more PFALs will become profitable.

Sensitivity analyses [76,90] on ROI and net present value (NPV) conclude that VPF profitability is sensitive to crop price, energy price, PPFD, and yield. This helps apply the Pareto principle suggested by [86] for working on the most impactful actions to profitability.

Business Planning Spreadsheets and Software

A Japanese PFAL [86] provides the most comprehensive analysis through spreadsheets on operational productivity and cash flow based on a discussion with 20 practitioners and scientists. The emphasis is for the reader to fill in the tables as they provide a hypothetical example of a closed-PFAL growing lettuce as a framework for operators. Users can understand and compute their farm's critical aspects and payback period. The business planning sheets actively encourage readers to analyse the best-case and worst-case scenarios to provide realistic ranges on the payback period [63].

Vendors use business planning spreadsheets to assist potential customers [188,206,207]. Although one vendor's projections are based upon a PhD thesis [206,208], they will be difficult to reproduce in a commercial context as the values were from a greenhouse. These issues are elaborated on within the projected yields section. Agritecture Designer is a commercial economic estimation tool that helps entrepreneurs build financial models based on 100 consultancy projects, but algorithms and underlying data are neither disclosed nor peer-reviewed due to their commercial nature [84]. It is helpful to estimate yields, costs and payback periods as a starting point, but trusting such projections is up to the user's discretion.

Greenhouses vs Vertical Farming

Recent analyses seem to suggest vertical plant farms are cost-competitive with greenhouses, finding hypothetical costs of growing leafy greens and herbs to be more profitable in PFALs [85,91]. However, these two analyses are not without flaws, and their conclusions are therefore invalid.

There is an omittance of depreciation in Eaves & Eaves's (2018) study, which is an issue as expensive lighting is used for 16 hours/day and will depreciate more quickly than in a greenhouse [85]. [85] also assumes a semi-closed-PFAL with minimal HVAC requirements (0.4% of OpEx) [85]. Moreover, it is assumed that yields are the same per unit growing area, which is not the case with increased crop density in PFALs as plants compete for resources with less air circulation and light. PFALs produce more per square unit of floor area but not necessarily more per square unit of growing area. Avgoustaki & Xydis's (2020)'s calculations for highlighting a doubling of yield biomass of basil for PFALs compared to greenhouses are also based on several studies [209–211], but the studies referenced do not validate that statement.

Unrealistic space utilisation (SU) seems to be a reoccurring issue, neglecting floor area for walkways, maintenance, processing, etc.) [103]. SU (%) is calculated by dividing the unit area of growing systems by the unit area of the facility building/structure. Avgoustaki & Xydis (2020) utilise 50% SU for a PFAL and 40% for a greenhouse [91].

Eaves & Eaves (2018) utilise 70% of the greenhouse and PFAL [85]. The SU for a greenhouse can range more realistically from 60-90% [212] and 50% for a PFAL [115]. In the case of Avgoustaki & Xydis's (2020) greenhouse [91], a realistic 75% SU would result in a yield boost of 87.5%, making the greenhouse more competitive than this comparative article suggests. For Eaves & Eaves (2018), 70% SU for the PFAL is probably too high and would require expensive mobile racking or automated set-up [85]. Eaves & Eaves report greenhouse profits to be only $9400 less than the PFAL; therefore, a 20% reduction in SU would turn the tides in favour of greenhouses [85]. [91] also cites [213] stating that initial investment for PFALs is 1500% of a greenhouse's CapEx requirements, yet the total CapEx cost is only 149% of the GH in their analysis.

These overlooked assumptions mean PFALs are not as profitable as suggested. Further validation is required before concluding that the PFALs are "much more profitable than compared to the greenhouses" [91]. Greenhouses already have a proven track record and are considered much lower risk. Both analyses provide a benchmark to compare against and Avgoustaki & Xydis' (2020) cash flow analysis to examine the viability of different financing structures is important. A comparison of two validated case studies of a greenhouse and PFAL growing the same crop is needed for a fair comparison.

Projected Yields

Projected yields are integral to economic modelling for VPF, but it is not as obvious as researchers may assume [193]. Several use vendor spreadsheets [188,206]. Interview results [69] suggest that VPF systems rarely meet the projected harvest yields from vendors, requiring a margin of error [69] for labour workflow issues [69,214], lack of growing experience [69,78], nutrient imbalances [69] and other potential issues that might hinder plant growth. Although, the yield and quality generally do tend to improve with experience and fine-tuning [69]. Generally, crops produced in VPF still shrink and have some waste; therefore, net yield does not always translate to edible yield that can be sold to the customer. This is rarely mentioned. The learning curve to improve yield and quality and reduce waste has only been integrated into economic analyses in two cases [84,146]. Tracking this in future economic studies would be helpful as it can vary from 5-30% wastage, tending towards 5% after several years with growing experience [69,215]. Miscalculating waste could make or break a farm's financial case.

Being realistic with the annual yield as VPF becomes a more established practice with standards will become more accessible, with farms achieving higher quality and consistent yields. A big challenge for economists is the lack of comparable data for yields of different crops. A commercial economic estimator, Agritecture Designer, has the most comprehensive data set for crops in different hydroponic VPF systems, although it requires validation to be a reliable source [84]. Some use extrapolated greenhouse data for yield per square unit area, neglecting that this is a function of the number of towers or stacked layers within a given space [76]. Other analyses include crops like potatoes, carrots, and radishes [36,76,103,192] without reliable data.

Risk and Uncertainty

Given the scepticism regarding the economic viability of VPF, developers and investors will struggle to commit to the development of a VF without financial cases supported with risk analysis or budgeting. Acquiring funding has been identified as the most significant challenge by operators [42] implying a disconnect between the information farms have and what investors want. As it stands, only a handful of analyses model any form of probability [36,75,192,216]. The rest rely upon deterministic calculations, which will provide an estimate of costs but likely lack the accuracy and confidence possible to sway many investors.

A study that I conducted engages with risk analysis using probability bounds analysis and first-hitting survival models to deal with uncertainty and develop a financial risk model [146]. I integrate qualitative risks from interviews but require further research for better risk data. Another study uses basic probability distributions to model unit costs and price points on high, medium, and low OpEx [36]. The central limit theorem is also used to compensate for the lack of yield data to model a multi-storey PFAL [192], assuming normal distributions for all yield values; however, no reference is provided. Providing inadequate or dated references seems common and lacks the rigour to validate such estimates.

The study exploring the future generation of VF [102] utilises even cruder ways of dealing with risk and uncertainty by applying rough margins varying from 10-30% to reflect uncertainties on the cost components. However, there is a clear need for more reliable probabilistic economic analyses for CEA and VPF due to the vast uncertainty.

It is almost impossible to accurately predict future cashflow, especially using deterministic methods. However, risk assessment tools such as Monte Carlo simulations [217] and probability bounds analysis [218] are tried and tested methods for various disciplines like engineering, ecology, and field-based agriculture. Uraisami (2018) states that sensitivity analyses and a risk scenario approach are essential and require industry-wide research and cooperation (involving horticultural scientists, PFAL operators, manufacturers of equipment, etc.) to provide financers with the information they require [86].

Automated Machinery

As far as the authors are aware, despite an increase in the number of conveyor automated PFALs serving the market [142,219–221], no analyses examine the cost-savings of automated and semi-automated systems. One study [216] assesses the economic feasibility of "automated" VPF in Turkey using fuzzy logic; however, they only consider basic automation, which is not costed, and software-sensor connectivity is supposedly "available for free". Cost-benefit analyses with production outputs would benefit researchers and operators in a market quickly saturated with technology and software solutions.

Economies of Scale

Until recently, no studies paid any attention to the economies of scale in VPF and PFALs, a major void in the research. Zhuang et al. (2022) published the first examination of economies of scale alongside the most extensive compilation of construction and CapEx data from 26 mixed PFALs (hypothetical and built) [194]. The study concludes that unit construction cost declines by 55% when the PFAL scale increases by 10,000% and the minimum break-even scale is 40 m^2 for lettuce (viable) and 100,000 m^2 for strawberries (unviable). The challenges are reliability when using hypothetical data, as SU plays a vital role in the analysis and some of the auxiliary data are the studies criticised for SU earlier [85,91]. Fortunately, most of the data is based on constructed projects and checked by experts in this area. This work is a serious contribution to the field. There remains a research gap in addressing the fundamentals of microeconomics of VPF, such as maximising profit and average cost curves to assess the economics of scale for OpEx [194].

2.6.5 Economic Review Summary

VPF economics research is still in its early stages, with around 42 analyses (October 2022].

CapEx is typically driven by lighting, racking/growing system and building costs. The production costs primarily consist of electricity, labour and depreciation. A detailed breakdown of capital or operational costs is rarely given in the same analyses, compounded by the dynamic evolution of associated technology and lack of standards. Therefore, a cross-comparison between OpEx and CapEx is difficult. Sensitivity analyses determine that electricity price, crop price, sunlight contribution, PPFD, and LED fixture efficacy are highly influential parameters on profitability. PFALs are starting to become more cost-competitive with an increasing number of profitable operations, according to industry surveys.

The ideal research would examine economics based on real-life case studies rather than hypothetical ones requiring speculative figures. This would provide a credible foundation for literature to build on. In addition, computing with uncertainty techniques can help develop more accurate cashflow projections to improve accuracy, model uncertain parameters and introduce risks.

2.7 Conclusions

The terminology around vertical farming is ambiguous, with no agreement on standard definitions. Comparison between farms has therefore been stifled. Clear definitions and classifications are required to advance standardisation, economic research, and crop growing recipe algorithms for this complex sector. This review provides updated terminology for vertical farming, plant factories, and indoor farming, recognising other food types grown vertically. Vertical plant farming is the more appropriate term for describing growing plants using the vertical dimension via multi-tier racks or vertically inclined surfaces. Moreover, indoor vertical plant farms with no solar light are better described as plant factories with artificial lighting (PFAL) to bridge existing literature where plant factory is predominantly used. A classification for plant factories on a spectrum of openness to heat exchange, gas exchange, and radiation is proposed: vertical plant factories with solar lighting (PFSL), open-PFAL, semi-closed PFAL, and closed PFAL.

A typology is detailed for all vertical plant farm configurations, including but not limited to farm placement, building integration level, system type, equipment layout, degree of automation, and location. This is the first time all available configurations are presented and defined in the same study. To date, the most popular commercial VPF models are semi-closed and closed-PFALs, that utilise NFT, DFT or a hybrid of both growing techniques. Typically, equipment is laid out as vertically stacked horizontal systems (sometimes with rotation implemented to maximise space utilisation). Basic automation and increasingly conveyor automation is used for VPF, but no farms have completed adaptive automation yet.

Vertical farming has a unique opportunity to disrupt how food is distributed from farm to table, and three distribution models are recognised: point of consumption, point of distribution, and point of purchase. Furthermore, business models in the VPF sector are identified, grouped and explored with regard to their strengths and weaknesses with relevant examples. Retail, wholesale, and farming-as-a-service models have been the most popular and visible to date. In recent years, emerging businesses growing fruiting crops, medicinal plants, and plant breeding are beginning to commercialise, and more research is required on these models. Vertical farms can also be positioned in urban locations, making the hybrid social enterprise model an area of high interest for providing social value.

This typology focuses on vertical plant farming. However, it can also be easily adapted to vertical farming for other food types by swapping the farm classifications, food types, system types, and lighting systems.

The number of profitable vertical plant farms has been increasing, with roughly 46% (n=494) reporting profitability in 2018-2019, up from 26% (n=231) in 2014-2017. If positive trends continue in LED lighting efficiency, labour efficiency, market demand for local food, crop quality and yield, more farms and crop types will become profitable.

More research into the economics is sorely needed to inform economically viable and scalable configurations. The economic analyses to date have been disparate and unbalanced, most of which are hypothetical. Therefore, it is impossible to give a balanced assessment of this emerging sector. The classification system is used to identify the farms in the existing analyses, and each is explored for its insights and caveats. Conclusions claiming PFALs are more profitable than greenhouses are disproven. Uncertainty in data is compounded by rapid technological, economic, and market changes. Risk and uncertainty quantification is seldom used but can bolster such analyses to compensate for the weak datasets for vertically grown plants (most of which use extrapolated greenhouse data) and the lack of benchmarking data. There are a few exceptional and comprehensive analyses assessing the economics and scale of Japanese PFALs, but validated datasets outside of Japan are still needed. None of the analyses considers conveyor automation becoming increasingly popular in the industry.

There is no general formula for profitability when there are many physical and technological structures and various combinations of crops, business models, and automation. Flexible economic analyses with uncertainty quantification can be immensely valuable to allow potential entrepreneurs and investors to identify viable farm scenarios confidently. The proposed typology can now be used for future analyses to categorise farms and their datasets properly. This could also inform standardisation and benchmarking efforts. More publicly available and real-life production and financial data are vital for advancing economic research in this sector with practical application.

CHAPTER 3

DECISION SUPPORT SYSTEM FRAMEWORK

FRAMING

The decision support system (DSS) framework presented in this chapter was my first journal publication, providing an overview of the core research plan for the PhD project, which I developed after identifying the main limiting factors discussed in Chapter 1. The review in Chapter 2 informed the challenges associated with economic estimation and standardisation. The overview in this chapter covers all the aspects of developing software that could assist entrepreneurs in their decision-making and developing their vertical plant farm business plans without reliable data.

The paper covers the main decisions entrepreneurs must make when planning their farms. It describes a workflow for economic estimation and risk assessment that can be used for iterative scenario analysis. The proposed software would address these decisions and be informed by equipment specifications, collaborative data-sharing, expert-elicited data and imprecise data techniques. The software architecture is presented alongside mock-up graphical user interfaces to highlight the functionality and use cases. This framework was the foundation of the research which then branched into realising the various components: i) the interview study (Chapter 4), ii) labour efficiency guidelines (Chapter 5), iii) financial risk assessment (Chapter 6), iv) environmental impact assessment (Chapter 7), and drivers of DSS adoption (Chapter 8). Today, the open-source prototype is available at: https://github.com/GaiaKnowledge/VerticalFarming. Further work in consortium building and software testing and development is required to realise the software commercially.

The study uses the term vertical farming instead of vertical plant farming, as it was written before the completion of Chapter 2. However, the model could be adapted to other farm types..

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The contributions of the authors are the following: F.B.D.O conceptualised the research idea, F.B.D.O. designed the methodology, F.B.D.O. designed the decision support system, F.B.D.O. generated the figures, F.B.D.O. wrote the paper, and F.B.D.O. R.D. reviewed the paper, F.B.D.O. edited the paper, and S.F., R.D. supervised.

Scott Ferson and Ronald Dyer individually consented to the use of this publication within this thesis.

A Collaborative Decision Support System Framework for Vertical Farming Business Developments

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3.1 Abstract

The emerging industry of vertical farming (VF) faces three key challenges: standardisation, environmental sustainability, and profitability. High failure rates are costly and can stem from premature business decisions about location choice, pricing strategy, system design, and other critical issues. Improving knowledge transfer and developing adaptable economic analysis for VF is necessary for profitable business models to satisfy investors and policy makers. A review of current horticultural software identifies a need for a decision support system (DSS) that facilitates risk-empowered business planning for vertical farmers. Data from the literature alongside lessons learned from industry practitioners are centralised in the proposed DSS, using imprecise data techniques to accommodate for partial information. The DSS evaluates business sustainability using financial risk assessment. This is necessary for complex/new sectors such as VF with scarce data.

3.2 Introduction

3.2.1 Background

Feeding a predicted 9.8 billion people by 2050 [222] on a planet stressed by climate change, water scarcity, soil degradation, ageing rural populations, and rising levels of urbanisation, will require constant innovation in resilient farming methods to increase food production by 25%-70% [14]. Key problems with traditional agricultural methods include (i) its use of 70% of the world's freshwater, 60% of which is wasted due to inefficient irrigation [223], (ii) its loss and waste of an estimated 33% of all food [224], producing 8% of global greenhouse gas emissions [225], and (iii) food contamination accounting for 600 million people falling ill, 420,000 people dying and $95 billion annually in lost productivity [13]. A relatively new concept in the field of urban agriculture (UA), vertical farming (VF), has arisen as a method to engage with the challenges by producing local, consistent quality and pesticide-free nutritious food all year round. VF is defined as the practice of hydroponically cultivating crops indoors in vertically stacked layers or inclined surfaces. Figure 3.1 delineates the concepts of UA, indoor farming and VF, and how these classifications may overlap.

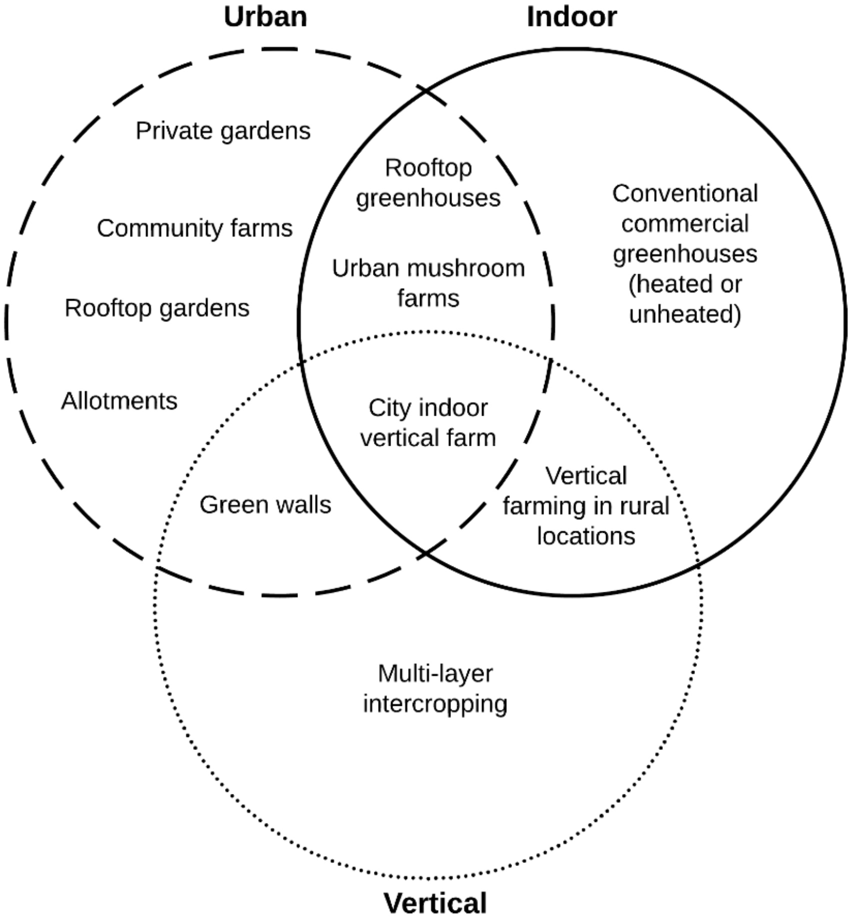

Figure 3.1. A Venn diagram to classify agriculture according to whether it is urban, indoor or vertical, or a combination. Adapted from [226].

Modern vertical farms utilise indoor farming techniques to take advantage of controlled-environment agriculture (CEA) technology within structures such as shipping containers, warehouses, purpose-built plant factories, greenhouses on rooftops or the ground, facades and under-utilised basement spaces [18,38]. Using CEA processes, environmental factors can be finely tuned for optimum growing conditions which are commonly called “crop growth recipes” [227]. Technically, it is possible to grow any crop vertically, but due to the high energy ratio required for edible matter, the most common crops grown are leafy greens, salads, herbs, microgreens, some vine crops, bio-pharma ingredients, and small fruits [61,62,228]. There are numerous benefits of VF when compared to conventional agricultural methods:

1. Minimising horizontal space requirements and increasing yield per unit area [49],
2. Reducing dependence on pesticides or herbicides [41],
3. Cutting water consumption by approximately 70%-95% [33,50,51],
4. Producing reliable year-round crop in soil-less environments independent of weather [33],
5. Reducing the necessity for storage, transport and refrigeration by local production [33],
6. Increasing food safety through reduced variabilities of wildlife and increased traceability [33],
7. Reducing direct dependence on fossil fuels by operating electrically [33].

3.2.2 Vertical Farming Markets and Industry Challenges

Over the past decade, powerful new technologies have enabled substantial growth in the VF sector. This is primarily due to the reduction in operational expenditure (OpEx) and capital expenditure (CapEx) from advancements in light-emitting diode (LED) technology, automation, and sophisticated greenhouse technology [78,229]. Figure 3.2 shows the trajectory for market growth over the next 6 years based on market research reports [230,231,240,241,232–239].

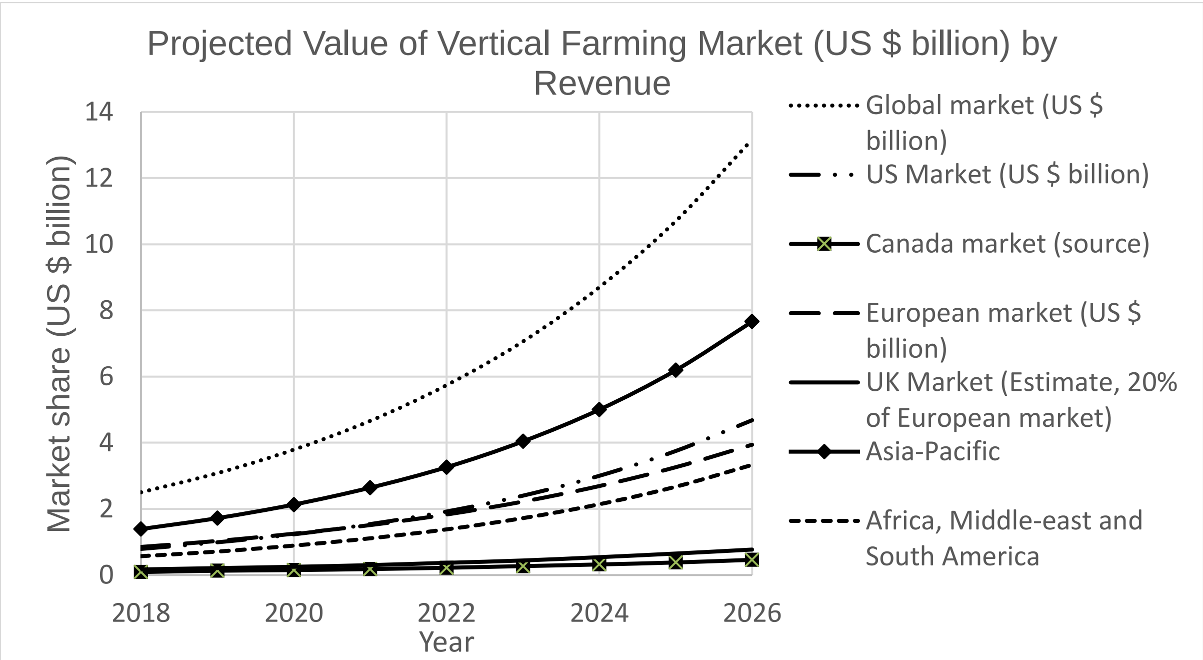

Figure 3.2. The expected market growth for VF by revenue from aggregated values and averaged compounded annual growth rates values (see text).

Despite an initial boom in the VF sector, the practice has struggled to be widely adopted without a trained workforce [77,78,229]. VF is rightly met with scepticism due to its limited crop choice, high energy demands from artificial lighting, high CapEx demand for equipment and real-estate and financial uncertainty [62,77]. Economic viability has been identified as one of the largest obstacles to realising VF projects [76], and whilst it has been reported in prominent surveys that there are existing profitable operations [61,62], the learning curve is steep and the financial risk is high. The sector is littered with failed start-ups that have struggled with (i) cashflow problems [37], (ii) underestimated labour costs [78], (iii) lack of adequate VF knowledge and accessible education [78], (iv) inefficient workflow and inadequate ergonomic design consideration [77,78], (v) low profitability margins [77], (vi) costly equipment failures [71,78] and (vii) poor early decisions around pricing, crop selection and location [78,242]. Preliminary results indicate about 85% of food-focused vertical farms fail within several years without further capital investment [70]. Projects struggle to realise an acceptable return on investment (ROI) above 10% for investors [77]. These failures are more acute because of the high CapEx investments. Paul Gauthier, a researcher from Princeton University's Vertical Farming Project concludes: "Vertical farms might work as a technical concept, [but] thriving as a business that transforms agriculture is another matter." [77].

Due to the risk and investment required, there is naturally some secrecy around business models and lessons learned [77]. Projects have received large investment rounds but in some cases insiders complain it is mostly "smoke and mirrors" [72,180], implying the route to a viable business may not be clear cut. However, some organisations are realising that collaboration will be crucial for its success [77,79,80] and academic research is needed to support the emergence of the sector [30,76]. VF requires a complex "urban food-water-energy nexus" approach [243]. This approach has been widely recognised as important for sustainable development, requiring cross collaboration among researchers in business, academia and government policy analysis not commonly seen in urban planning and design [243].

Currently, detailed financial analyses of CapEx, OpEx and revenues have been hard to produce, due to the complex nature of combining architecture and agriculture [76]. Calculations tend to be for a particular scenario, and they are difficult to generalise [76]. From an investment perspective, a clear plan for profitability is required [191].

"As a novel form of agriculture in many parts of the world, most CEA operators are struggling to raise the funding they need. In order for this to change, best practices that boost the confidence of investors need to be more accessible so that they can identify the winning models with confidence and keep investment deal flow." - Henry Gordon-Smith, Founder of Agritecture, from CEA Census 2019 [61]

Investors are beginning to recognise vertical farms are a long term play and require patient capital. What can be done to reduce the barriers to entry and ensure sustainable growth of an incipient industry still finding its feet? Two clear needs are i) bridging the knowledge between various sectors (such as lighting, greenhouse management, architecture, policy, etc) and ii) developing a robust and flexible economic analysis [76].

3.3 Decision Support System Solution

One proposed solution is a decision support system (DSS), acting as a hub for compiling lessons learned with an adaptable economic model library to produce financial risk assessment under uncertain scenarios. Such a tool could aid the formation of a robust business model with only partial information available and inform financial investors to make more reliable investments, increasing confidence levels. This is needed for the industry to grow sustainably as the technology begins to mature and should evolve quickly with the most recent advancements. A start-up has an excessive amount of decisions to make around systems selection, zoning codes, compliance, location, pricing, environmental control and the list continues. These options change quickly and solutions are scattered. There is a large demand for technical expertise as the industry is still relatively new and lacks standardisation [61]. The proposed DSS aims to centralise this information and simplify the business planning process. This paper is structured by the following objectives:

1. Identify the related works from industry and academic sources to describe the breadth of decisions that can be made for VF developments, and review relevant software and DSS solutions (Section 3.4).
2. Describe and illustrate the combination of techniques used for the DSS model library: (i) structured expert elicitation protocols (ii) imprecise data analysis techniques (iii) adaptable economic model and (iv) risk assessment from user-input scenarios (Section 3.5).
3. Present the proposed DSS through illustration of its architecture, description of its relevant components, and use of graphical user interfaces (GUIs) with Liverpool used as an example to demonstrate the functionality of user-inputs, farm design, risk management, product choice and more (Section 3.6).

4. Conclude with the key drivers for profitable business models and further work to be done to realise the DSS as an available software (Section 3.7).

3.4 Literature Review

The literature review covers four sections: i) a broad overview of common-use cases for the DSS, supported by a short critique of the economic analyses in the literature; ii) lessons learned from DSSs for agriculture; iii) functionality of indoor agricultural DSSs and application to VF and iv) limitations of commercial software for VF. The aim of this review is to understand the gap in research and industry that the proposed framework can address, embedding insights and guidelines from previous projects to improve likelihood of success.

3.4.1 Vertical Farm Configurations and Decisions

There is a plethora of decisions to be made around building types, business models and configurations of vertical farms. The choice of lighting solutions and VF equipment (both turnkey and bespoke) can be overwhelming and requires an interdisciplinary skill set. A lot of the equipment is expensive and therefore the capital risk for entrepreneurs is high. [18] collates and reviews the technologies and decisions with a comparison of the economic analyses conducted to date. The review utilises common-use case studies to propose a typology for VF systems and business models. The typology is used to outline design options in the DSS framework proposed in this paper. [76] argue that researchers must collaborate with existing small-scale pioneers of vertical farming to develop and refine increasingly accurate cost models [76]. A clear route to profitability is recognised by practitioners and researchers as a requisite step to enable financial investment and inform policy-makers [36,76,77,228]. [18] concludes that from all the economic analyses conducted in the literature for VF, only one attempt, "VFer" [76], has been made to provide flexible and adaptable economic analysis for various farm configurations. VFer is used to calculate costs and potential ROI for a vertical farm from several typical VF configurations and using locational data. However, none of the economic analyses from the review include significant uncertainty in ROI estimation [18]. The DSS proposed in this paper builds upon the framework of VFer to include turnkey hardware solutions, provide more accurate estimations and embed risk and uncertainty quantification.

3.4.2 Relevant Decision Support Systems Literature

Decision support tools are an important part of evidence-based decision-making in agriculture, helping to improve productivity and environmental outputs [244]. For farmers and their respective advisers, DSSs can help facilitate effective farm management by making scientific knowledge and rational risk management algorithms accessible [245]. They also enable efficient recording of data which can be automatically analysed to generate empirical recommendations and alerts. [245]. Two key reviews have been conducted on agricultural DSSs: 11 years ago on 70 crop protection DSSs in Europe [246] and 15 years ago on a taxonomy of all 624 DSSs in published works at the time [247]. These both identify the various functions and common-use cases. A clear insight was that the interpretation of uncertainty should be distributed between the DSS developers and the users. Uncertainty quantification is required to account for variability in data, known imperfections in models, weaknesses in expert-algorithms, etc. [246]. Manos et al. (2004) also concludes that the planning and development processes in the agricultural sector constitute a multi-complex problem that is difficult to solve, if not faced thoroughly [247].

Despite interest from producers in ways to reduce uncertainty in decision making, many DSSs have struggled with under-utilisation in practical agriculture due to both technical limitations and farmers' attitudes [245,248,249]. This has been labelled the "problem of implementation" [245]. Rossi et al. (2014) have identified solutions to overcome the short comings of previous DSSs [245]:

1. Focusing on important problems with a holistic approach
2. Using automation and integration in data collection
3. Developing and validating fit-to-purpose mechanistic, dynamic models
4. Designing a user-friendly interface and providing complete and easy to understand information
5. Delivering the DSS through the web to enable continuous updating and improve accessibility
6. Designing to aid the decision-maker and not replace them by providing rationale
7. Involving end-users in the development of the DSS to obtain insight into how users make decisions
8. Communicating benefits of DSS via seminars/site-visits
9. Involving other potential stakeholders
10. Developing a communication mode with end-users i.e. combining "push" and "pull" systems

One challenging decision for farms is setting a fixed price for crops [250] which strongly influences the ROI of vertical farms [76]. This requires collaborative planning across different farms and recent research recognises the implementation of collaboration mechanisms to drive sustainability within fruit and vegetable supply-chains [251]. One DSS has been developed by [252] to engage with the lack of research addressing collaborative planning issues in conventional agriculture [253,254]. The collaborative mechanisms proposed by Zarate et al. [252] are equally necessary for indoor farming and VF if it intends to provide cities with an alternative source of food.

3.4.3 Indoor Farming Decision Support Systems

There is a wide pool of DSS literature for greenhouse management that could be adapted for small-scale vertical farms (see [255]). The management of production in a greenhouse is similar to indoor vertical farms and requires decision making on many tasks and time scales [255]. Decisions are primarily related to management of crop growth conditions, irrigation and propagation [255–259]. Greenhouse growers also use prediction tools for disease, yields, production planning, pest management, and cost-benefit analyses [255,260–262]. None of these DSS systems adapt to help with the setting up of a farm within an urban context [247]. A study by Shamshiri et al. [255], based on the review literature, concludes that more accurate economic analyses and justifications of the high start-up costs are required before large-scale commercial VF developments can be realised.

3.4.4 Vertical Farming Software Solutions

Some companies and suppliers of VF systems use in-house software for deterministic projections of ROI and yields which they share with their customers. In an informal email survey of VF system vendors (n=5), none used randomness in their customer spreadsheet model, but all agreed it would be beneficial. Yields may be improved over the course of operations, especially as many newcomers in the VF space lack any agricultural experience [61]. Incorporating the learning curve of a VF would be preferable to assuming a best-case or conservative yield and ROI projection. This can aid decision-making with more accurate forecasting. Most of the commercial software has been developed within the past 4 years or is in beta-testing and development. They support farmers to achieve various aims: planning, cultivation management, operational efficiency improvements, internet-of-things (IoT) connectivity and post-harvest sales. A summary of VF and high-tech indoor farming software is provided in Table 3.1, excluding in-house proprietary software developments by vertical farms (see for example BoweryOS [142]). They appear to address some of the implementation problems discussed in the literature by beta-testing for user-feedback, automating and integrating various systems for data collection using IoT technology and providing web access to enable continuous updates. The solutions that are available are subscription based.

One software, Farm Road, is a farm management platform for integrated data-driven farming that connects with suppliers and buyers. It is the first attempt to try and unify several platforms with different aims for CEA, starting with: Autogrow, Native and The Ridder Group. Another software, Artemis, is an established pre-harvest platform for large scale CEA that helps with compliance, key performance indicators, task management and visualising farm data and tasks. The software developments mentioned tackle cultivation management and sales, but only one recent development, Agritecture Designer, begins to engage with planning and financial feasibility by utilising industry consultant expertise. It is currently in beta-testing and shares similar goals to the DSS proposed in this paper.

Table 3.1. Software tools for VF practitioners

Software	Description	Organisation	Availability	Cost	Year	URL/ref
Artemis Cultivation Management Platform	Enables growers to optimise facilities for profitability and reduce risk. A pre-harvest solution	Artemis	Yes – for farms >1 hectare growing area	Unknown	2015	https://artemisag.com/
Agritecture Designer	First digital platform built for entrepreneurs planning urban farms	Agritecture	No. Beta-testing	Unknown	2019	https://agritecture.com/designer
VFer	A flexible economic estimating tool for vertical farms	University of Nottingham	Not public	N/A	2017	[76]
Liberty Produce Innovate UK Future Farming Hub Project	Operational and technical improvement software integration	Liberty Produce	In development	N/A	2019	https://www.liberty-produce.com/
Farmee	Cloud-based digital service for monitoring, control, machine learning algorithms and global network of farm data. Provides digital expert consultancy service.	Farmee	No. Beta-testing	£50 per question	2018	https://www.farmee.io
PFAL D&M	Plant factory management and design software	Japan Plant Factory Association	No	N/A	2015	[263]
OpenAg Initative	Open-source crop growth recipes optimised for nutrition and flavour. Also have educational platforms.	Massachusetts' Institute for Technology (MIT)	Yes. Project terminated.	Free / Open-source	2012-2019	https://www.media.mit.edu/groups/open-agriculture-openag/overview/
GrowOS	IoT system connectivity for indoor farms	Grow Computer	Beta-testing – public release Fall 2019	N/A	2017	https://www.growcomputer.io/
Native	A post-harvest solution for real-time local supply chain integration, ecommerce engine. traceability, waste mitigation and ROI calculations.	Native ag	Yes – currently USA only	$99 per month	2018	https://www.nativeag.io/
FarmRoad	Collaborative unified management tool to integrate all farming data, crop recipes, set goals, connection with suppliers and buyers.	AutoGrow, The Ridder Group and Native	N/A – beta-testing	N/A – subscription based	2019	https://www.farmroad.io/

Some software projects have experienced problems. MIT's corporate funded OpenAg Initiative promised to build an open-source ecosystem of resources to accelerate digital agricultural innovation, but was closed due to allegations of academic dishonesty and improper dumping of wastewater [72,264]. This situation serves as a reminder of how little information is known about the true effectiveness of tech-driven indoor farming methods and the need for collaboration and transparency. OpenAg's datasets include crop growth recipes developed through machine learning techniques [265] as the inaccessibility of crop growth recipes was identified as a challenge in the sector. There seems to be a race for an integrated software solution that automates ideal growing conditions. However, there are an extensive number of set point combinations for environmental control. Factors that influence these combinations include crops/cultivars, phenotypical traits, plant design goals (nutrition, flavour and structure), light spectrum, temperature, nutrient composition and strength, and more. Eri Hayashi, vice-president at the Japan Plant Factory Association (JPFA) claims "It's almost impossible for growers and researchers to trial all the conditions. What is needed is a shared platform that is accessible for everyone who wants to contribute or needs the data" [80].

The commercial software available and in development address common struggles for VF, but they approach a complex problem in silos. Any new business would probably struggle to adopt many different software solutions due to the time and effort required to learn new tools and VF is no different. Although there is mention of risk from some platforms, there is no evidence to suggest risk and uncertainty quantification has been incorporated into the performance projections of VF software. There is a need for an open-source cooperative development to accelerate knowledge sharing and reduce the duplicative and costly efforts each company makes for research and development (R&D) [80]. Such an approach can shorten the innovation cycle and make the whole industry's processes more efficient. Learning from the mistakes made by OpenAg, the need for transparency and standardisation of data collection to ensure quality and scientifically robust data is paramount for such a development. There is no need to reinvent the wheel, as open data could benefit all growers and farms, but this requires a paradigm shift by practitioners towards cooperation [80]. Lastly, there is no available software to help specifically with VF business planning and financial risk. Agritecture Designer, in testing, may provide a solution to this but whether it functions well and is collaborative has yet to be confirmed. The need for a risk-empowered business planning tool remains to encourage reliable investments.

"As we are still in the initial stages of a promising indoor ag industry, we need more opportunities for knowledge/experience sharing, standardisation, education and collaboration to move the industry forward. More importantly, we need a more distributed network for innovation to work together to develop new innovation." - Eri Hayashi, Vice President of JPFA, as part of an exclusive interview for Urban Ag News [80].

3.5 METHODOLOGY

The core aim of the DSS is to provide a robust economic viability assessment, combining user-inputs with historical data gleaned from focused interviews and literature. It is the most complex element and is detailed within this methodology and rationale. This methodology is described into several sections: i) expert elicitation protocols for primary data collection from industry practitioners, ii) imprecise data techniques used to accommodate for scarce datasets, combining primary data from interviews, the DSS user's inputs and secondary data, iii) a profitability estimation model and iv) risk assessment using probabilistic methods. Secondary data used to inform the profitability model is sourced from available literature, open projects, equipment specification (for lighting, climate control and irrigation), surveys [61,62] and available crop growth recipes [265]. Example datasets include typical crop densities for a given space, optimal spacing between plants, typical operating costs and expected yields. Other location-related data is required by the user: market demand, climate for heating, ventilation and air-conditioning (HVAC) requirements, energy price, labour costs and more. These vary substantially depending on location [76].

Data on indoor growing challenges in the literature is limited, scarce and unique to a farm. There is no available data for occurrence of disease or pest outbreaks, market fluctuations or changes in yields over time in a business context. The methodology details how this missing information which informs the proposed model will be uncovered through interviews using a structured expert elicitation protocol, with example questions described. The imprecise data analysis used to interpret the interview data for more accurate forecasting is outlined. The mathematical model is broken down into steps for generating ROI with risk analysis applied for proposed or existing vertical farms. The imprecise data techniques enable the creation of an adaptable model library. Using machine-learning algorithms, this library continuously improves when given more information from DSS users about their farms to provide more accurate projections over time.

3.5.1 EXPERT ELICITATION PROTOCOL WITH OBSERVATIONS

For the DSS development, interviews are currently underway with VF pioneers, and associated businesses (lighting suppliers, indoor farms, R&D companies and system suppliers) worldwide. The data collection will highlight the gaps in knowledge, which will inform the holistic design of the DSS. The current lack of baseline data and standardisation across the VF sector can start to be addressed once preliminary data is collected. The focused and semi-structured interviews utilise a modified expert elicitation protocol 'Investigate-Discuss-Estimate-Aggregate' or IDEA [266], to mitigate contextual biases and improve accuracy where empirical data may be lacking. IDEA was selected as the appropriate protocol due to the financial and practical constraints of interviewing business and industry leaders. It can be adapted to incorporate remote elicitation, making structured expert elicitation accessible on a modest budget [266]. It involves several key steps using a modified Delphi procedure.

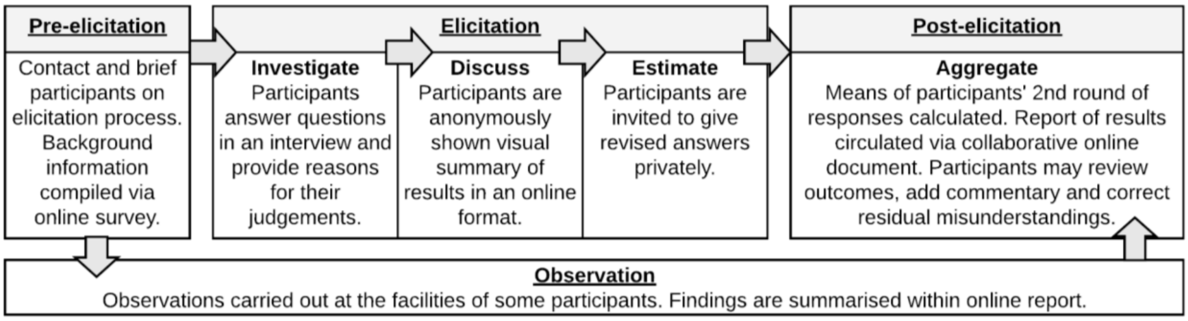

Figure 3.3. IDEA protocol with integrated observations adapted from [266]

IDEA protocol includes the three-step and four-step elicitation procedure (see example in [266]) to establish uncertainty bounds in the absence of hard data. This procedure asks participants to estimate upper, lower and best-guess values for certain parameters or frequencies (i.e. the amount of pest outbreaks on a farm since operating). Interview data are used to estimate important considerations such as time to peak operational performance, rate of yield increase (representing the learning curve) and fluctuations in yield at peak performance. This information is elicited by asking participants to draw and annotate a graph of their farm's average yields per harvest since the start of operations with associated level of confidence (depicted in Figure 3.4). If a participant is able to provide yield datasets from their farm, this will be weighted more strongly.

Participants are then asked to describe the graph they have drawn and annotate it with the following:

- Time taken to reach peak operational performance or current state

- Increase in yield from the start of operations to peak operational performance or current state (kg or %)
- Lowest yield since running optimally or at current state *
- Highest yield since running optimally or at current state *
- Average yield during running optimally or at current state *

* *signifies questions which have four-step question format applied in the absence of data*

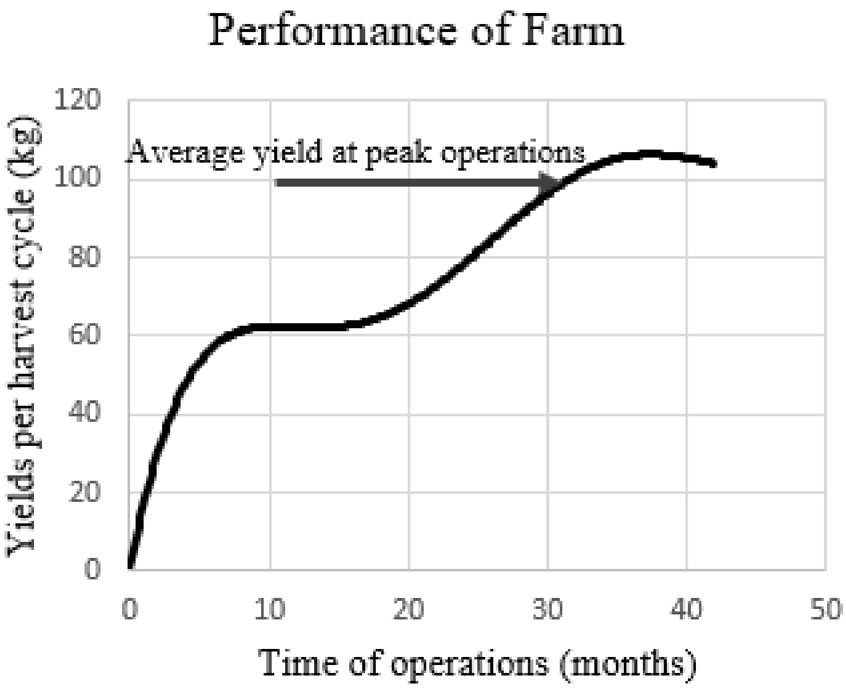

Figure 3.4. Relationship of average yield over time depicted by a participant

Responses from other questions within the interview inform estimates for labour costs, risk occurrence and start-up costs for various VF configurations. Qualitative questions inform the knowledge base of the DSS, including lessons learned and key considerations.

3.5.2 Imprecise Data Techniques

Due to the current scarcity of data, the imprecise probability technique of probability bounds analysis [267] is applied to estimate distributions from interviews and user-inputs. These techniques are applied to the data and user-inputs prior to being used in the ROI model and other models specified within the model library in Section 4. The analysis of collected data is used to establish uncertainty bounds that estimate distributions of time to reach peak operational performance of vertical farms (representing the learning curve), fluctuations in yield at peak performance and chances of pests of pathogen outbreaks. Historical data from case studies informs estimates for duration, costs and labour of developing VF projects. Probability bounds analysis is computationally faster than Monte Carlo and will bound the correct answer based on historical case-studies [267]. Most importantly it only requires partial inputs. It often produces optimal solutions [267] and computing with probability bounds allows modelling with significant uncertainty, which in this instance is used to calculate risk in business sustainability.

3.5.3 ROI PROFITABILITY MODEL

The core model assesses financial risk, focusing on the ROI model for profitability that has been created based on adaptions to equations developed from researchers as an estimation tool for vertical farms (see [76]). Figure 3.5. ROI profitability model utilising equations 3.1 to 3.9 for the risk assessment. illustrates how the model functions through a series of modules, although due to the many interdependencies inherent in growing crops indoors the visualisation has been simplified. The model interprets user-inputs on: (i) the local market, (ii) selected crops to grow, (iii) the volume and area of the farm, (iv) local climate data, (v) prices of foods, (vi) the type of facility, (vii) equipment used, (viii) rent, (ix) renewable energy produced at the facility they are using. The model can accept both partial information and complete information for further precision, projecting uncertain inputs throughout the rest of the model, as well as making assumptions for default values from the aggregated data typical of the VF type. The DSS can fill gaps in the user's knowledge whilst providing rationale to avoid replacing the decision-maker. Risks and uncertainty are applied in the model when predicting expected yield as well as potential market risks, such as a customer reducing their order quantity.

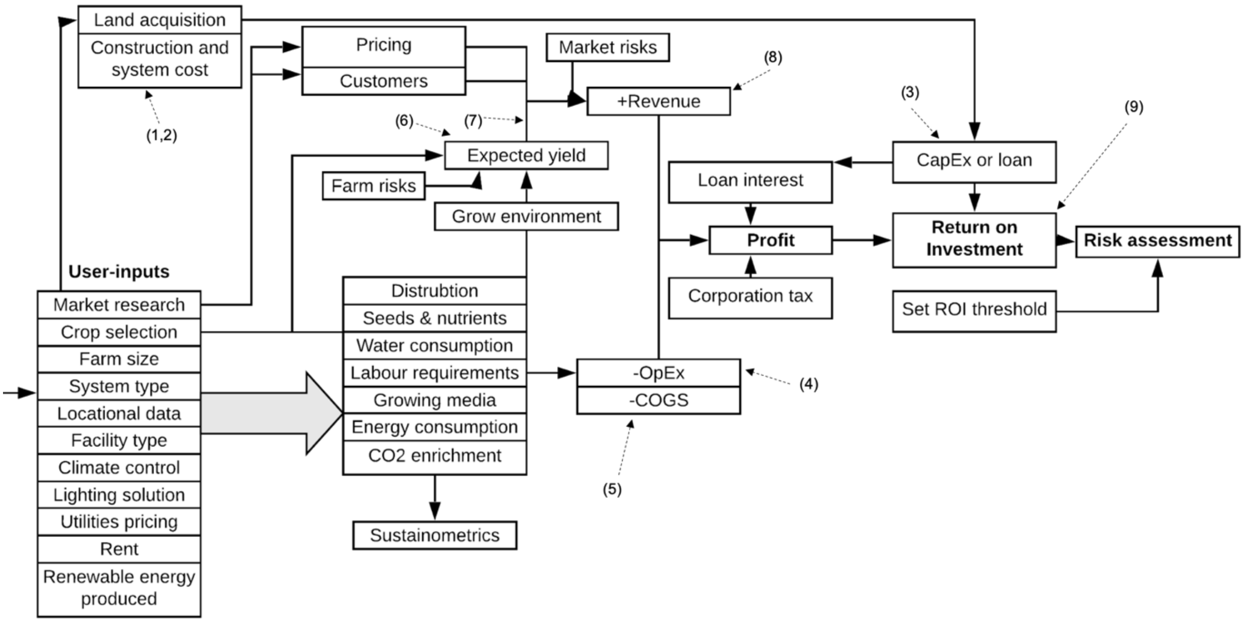

Figure 3.5. ROI profitability model utilising equations 3.1 to 3.9 for the risk assessment.

Equations 3.1 and 3.2 calculate the costs for construction and vertical farming system cost based on the farm design. Equation 3.3 Calculates the CapEx cost (see [76] for costing data) from sub-items which are highly user-defined. Where possible the DSS can provide suggested values from generalisations based on interview data on crops, system types and the farm-type. If the user knows the exact amount of CapEx for the project or a range, they can bypass this step.

$$\textit{Construction cost} = \textit{Structure cost} + \textit{Finishing cost} + \textit{Appliance cost} \tag{3.1}$$

$$\begin{gathered}\textit{System Cost} = \textit{Light cost} + \textit{Growing area cost} + \textit{Germination \& clean area cost} \\ + \textit{Irrigation cost} + \textit{Processing plant cost} + \textit{Waste management cost} + \\ \textit{Renewable energy implementation cost}\end{gathered} \tag{3.2}$$

$$\textit{CapEx} = \textit{Land acquisition cost} + \textit{Construction cost} + \textit{System cost} \tag{3.3}$$

Equation 3.4 calculates the OpEx cost either from user-inputs, or from generalisations based on crops, business model, funding mechanism and farm-type.

$$\begin{gathered}\textit{OpEx} = \textit{Lighting cost} + \textit{Climate cost} + \textit{Misc energy cost} + \textit{Water cost} + \\ \textit{Salaries} + \textit{Maintenance cost} + \textit{Rental costs} + \textit{Distribution cost} - \textit{Renewable} \\ \textit{energy} + \textit{Loan repayment}\end{gathered} \tag{3.4}$$

Equation 3.5 calculates the cost of goods sold (COGS). The parameters are determined by consumable costs and direct labour attributable to farm operations not on a fixed salary. Labour outputs will be affected by the experience of the farmer, this is reflected in the increased yield or drop in learning curve and not the cost of labour.

$$COGS = Seeds\ cost + Nutrients\ cost + CO_2\_cost + Labour\ cost + Packaging\ cost \quad (3.5)$$

The yield of a particular plant per harvest cycle is estimated by Equation 3.6 and has been adapted from VFer (see [76]) to compute yield per harvest, with adjustments for nutrients, humidity, light spectra, and risk and uncertainty included.

$$Y_a = Y_s \times N_p \times L_f \times CO2_f \times T_f \times H_f \times N_f \times (1 - F_r) \times R_f \quad (3.6)$$

The adjusted plant yield for a plant (Y_a) is calculated from the standard yield (Y_s) which is a value validated from the literature, multiplied by the number of plants (N_p), and various factors influencing its value [76]. This equation will become more precise and accurate over time as data informs the interdependency between the parameters. The factors influencing yield include:

1. Light factor (L_f) – The ratio of actual PAR delivered to the plants' canopy to theoretical PAR requirements. Adapted to include light spectra, which has been found to influence crop productivity more than PAR requirements according to industry leading grow light developers [268]. With artificial lighting, this value should be 1 if lighting is controlled at optimal level.
2. CO_2 factor (CO_{2f}) – The reduction of yield from insufficient CO_2 enrichment.
3. Temperature factor (T_f) – The reduction of yield caused by overheating or freezing of the grow area, especially if the farm is uncontrolled by HVAC or other systems. Value is set at 0.9 for preliminary estimation [76], but is assessed depending on the climate, level of HVAC control and the crop requirements.
4. Humidity factor (H_f) – The reduction of yield caused by exceeding or falling short of the humidity requirements of a crop. This is dependent on the crop spacing, type of crop and level of ventilation required. Value is set at 0.9 for preliminary estimation and is assessed depending on climate control system.
5. Nutrient factor (N_f) – The reduction of yield caused by inadequate nutrient intensity or mismatched nutrient composition. Value is set at 0.9 for preliminary estimation and is assessed depending on level of specific nutrient control and whether the farm has automated dosing in place.
6. Failure rate (F_r) – The failure rate of crops is influenced by mishandling, unsellable or damaged crops. This varies substantially as businesses and farmers become more experienced, and this parameter is informed by the learning curve measured from

interview data. This parameter encompasses a level of randomness lessening over time.

7. Risk factor (R_f) – The risks factor parameter represents issues that could destroy or damage a whole batch or harvest requiring a deep clean of the farm. Examples would include pest outbreaks, plant pathogens or compliance issue. This parameter is random but reduced when precautionary measures are implemented that mitigate the risk.

The income from a crop is calculated by Equation 3.7. This has been adapted from [76] to include different customer segments and to calculate per harvest cycle to allow discretisation throughout the model. The sum of all crop incomes are combined for a total plant income (PI) in Equation 3.8, which is multiplied by the number of harvest cycles per year to calculate annual revenue.

$$PI_c = P_p \times P_i \times Y_a \times PSR \times CSR \times N_H \tag{3.7}$$

The plant income per plant for a customer segment (is calculated by multiplying the following parameters by the adjusted yield computed from Equation 3.3:

1. Plant price (P_p) - The cost of the crop in the local market which is user-defined from market research or filled by a default value from the crop catalogue in the database.
2. Plant index (P_i) - The ratio that the price of products from the vertical farm are sold for compared to the average market price of the crop. Set at 1.25 if not specified by the user and based on claims from a world leading urban agriculture consultant that a farm can typically sell produce 20-30% higher than market price [269]. Noteworthily, crop pricing is extremely dependent on the local market. If the price is specifically known, a value can replace .
3. Price share rate (PSR) - The ratio of revenue shared between the farm and other marketing process (such as paid for advertising). Typically, this is much lower than rural farms due to the reduction in the food supply chain. If this is not adjusted by the user then it is automatically set to 0.6 assuming 60% of revenue is shared by the farm (three times higher than rural farms). [76].
4. Customer share ratio (CSR) - The crop may be sold to customers at different price brackets, such as wholesale or retail for example. This ratio represents the proportion of customers sold to at the price bracket or for a particular crop. Vertical farms typically spread their market across a couple of customer segments.
5. Number of harvests (N_H) – This income is calculated per harvest and is multiplied by the number of harvests to compute revenue for the duration desired by the user.

The revenue generated across all the different crops and customer segments is calculated from Equation 3.8. This equation is the summation of all the sources of income for each plant species, denoted as , and their associated customer segments denoted by . The revenue can be calculated per harvest, for a specified duration or per year in order to calculate the estimated ROI. The monthly revenue is calculated by the number of plants harvested per month.

$$Revenue = \sum_{c=1}^{cust.} \sum_{x=1}^{spec.} PI_{c,x} = \begin{pmatrix} PI_{cx} \\ \vdots \end{pmatrix} \tag{3.8}$$

Equation 3.9 calculates ROI by calculating profit divided by total investment, and then multiplying by 100 for a percentage. The profit is calculated as the revenue computed from Equation 3.5, subtracting OpEx (Equation 3.1), COGS (Equation 3.2), the interest from the loan or investment and the taxes associated with the specified operation. The user has several options that the DSS can compute: (i) the ROI for a tax-year from annual revenue; (ii) the monthly ROI and (iii) the payback period. All the options can have risk and uncertainty applied at the discretion of the user to visualise best-case, worst-case and all the scenarios in-between. The monthly ROI can be used to compute the risk assessment described.

$$ROI = \frac{Revenue - OpEx - COGS - Interest - Tax}{Total\ Investment} * 100 \tag{3.9}$$

Using the equations listed above, a required ROI can set by the user which increases with time and computes the price point required (crop pricing) to sustain a profitable farm operation.

3.5.4 Risk Assessment

To achieve a realistic economic forecast for a VF start-up risk and uncertainty quantification is essential. Stochasticity must be included in random parameters such as failure rate, improved yields over time, catastrophic risk and potential pest or pathogen outbreaks. The probability bounds for distributions are established in the database as user-inputs are analysed (expressed as bounds on cumulative distribution functions called "p-boxes"). Probability bounds enable risk calculations without requiring over-precise assumptions about parameter values or distribution shape [267]. P-boxes can also be used to model the event of bankruptcy after crossing a threshold defined as the first-passage time, used commonly in economics [270]. This approach is assesses the financial risk. Figure 3.6 shows an example financial risk assessment of a

VF, for which the p-box primarily falls within moderate risk category with some substantial risk until the five-year mark. The user is able to define the bankruptcy based on a specified ROI threshold required by investors for certain periods, i.e. a venture capitalist would typically look for a profitability of 10-20%+ [77]. If this threshold isn't met over user-specified duration, then this may be considered the criteria of "bankruptcy". The threshold for ROI may vary time, for example: -5% for the first 2 years; breaking-even after 3 years, 7.5% after 5 years and 10% after 7 years. The risk categories are proposed as follows (thresholds are illustrated Fig. 3.6 and Fig. 3.7), with the p-boxes showing the range of potential scenarios:

- *Critical:* 50% probability of bankruptcy within 3 years
- *Substantial risk:* 25% probability of bankruptcy within 5 years
- *Moderate risk:* 10% probability of bankruptcy within 10 years
- *Safe:* Less than 10% probability of bankruptcy within 10 years

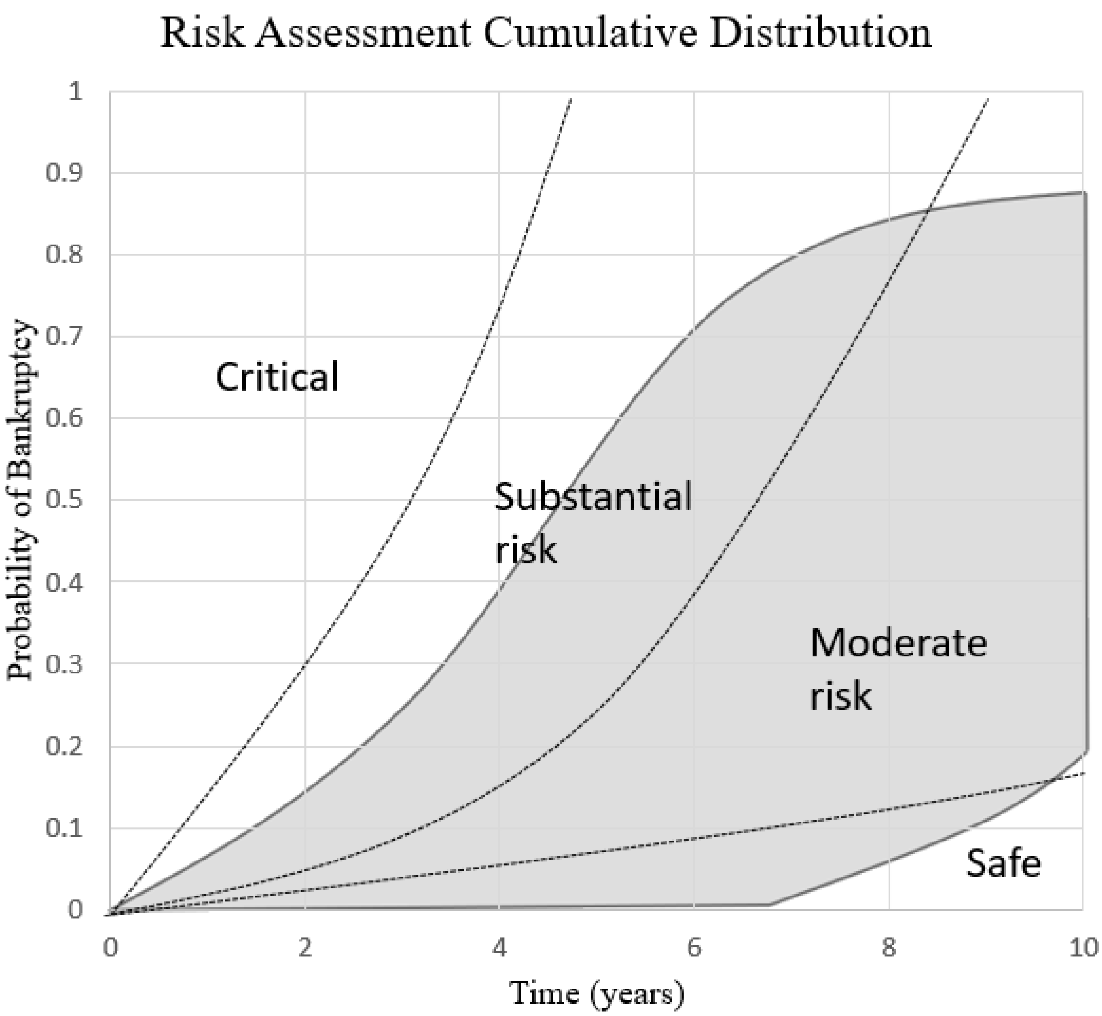

Figure 3.6. Risk assessment graph for the probability of bankruptcy with less precise parameters (cf. [271])

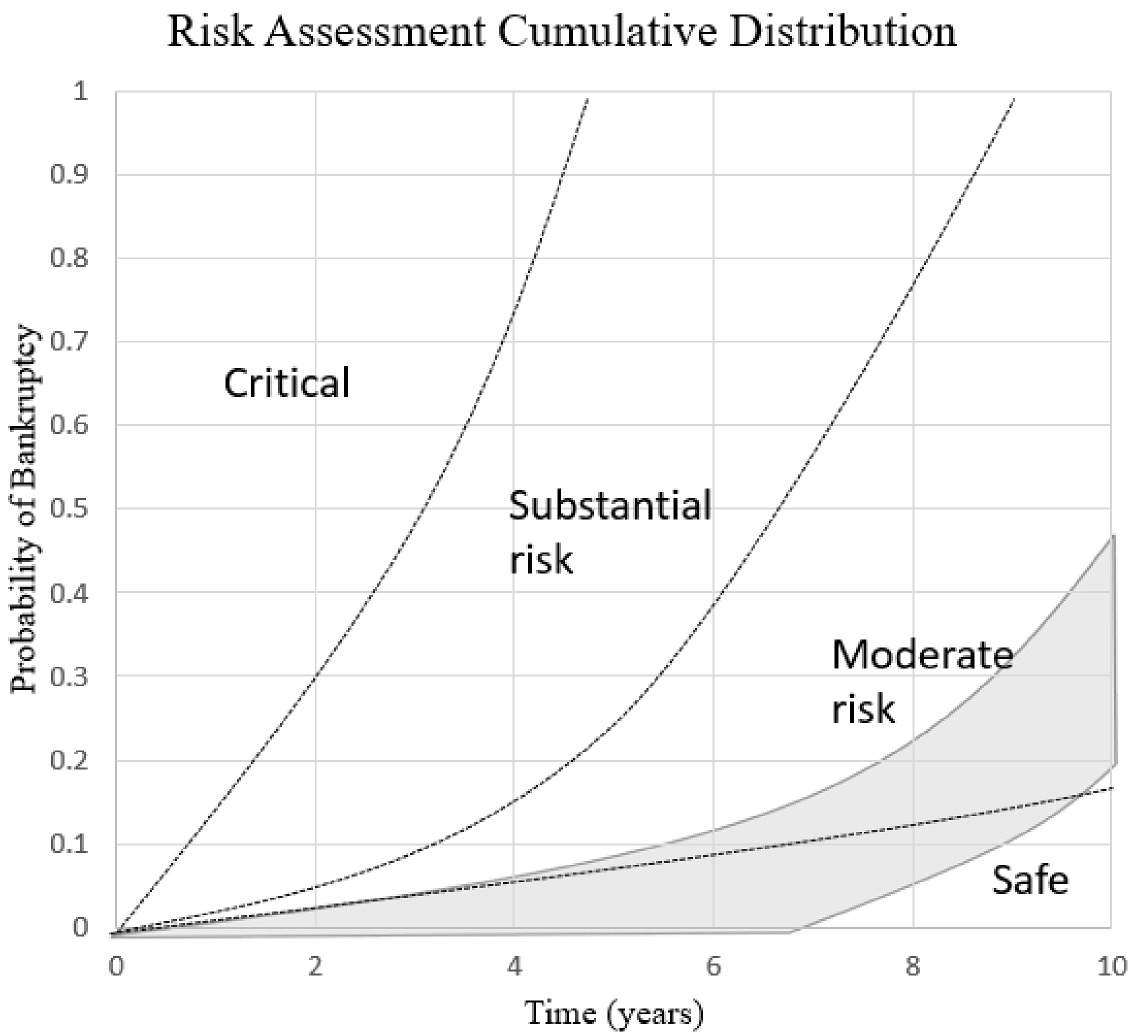

Figure 3.7. Risk assessment graph for the probability of bankruptcy with more precise parameter inputs (cf. [271])

Figure 3.6 initially shows how scarce data and imprecise user-inputs affect the potential economic scenarios that could unfold. As further information is gathered from interviews or the user inputs are more precise, the number of potential scenarios becomes smaller and more precise (Figure 3.7). By having a more precise output of the simulation, the user may discover the VF operation to be more moderate risk than substantial risk.

3.6 Decision Support System

3.6.1 System Process Structure

Many of the systems identified in the literature review engage with pre/post-harvest and yield optimisation. This DSS builds upon the preliminary work of "VFer" [76] planning and developing a profitable VF business, whilst providing a framework for continuous improvement. Some features are described that overlap with existing tools regarding sensors and data collection. Ideally such platforms would be cross-compatible and work with all hardware and software with IoT connectivity. The DSS facilitates better decision-making by utilising a database of historical data, a knowledge-base (KB) of best practices and case-studies, a model library (ML), and a user interface (UI).

The software takes users through a series of steps to begin conceptual development of a farm: planning (location, business model); farm space information and crop selection; farm system design and evaluating the resulting profitability (user journey is illustrated in Figure 3.8). The user may provide only partial information, which is to be expected. As the user iterates their business plan with different configurations, price points and so forth, they can identify the weaknesses in their business model and where they lack knowledge to make decisions. Sensitivity analysis can inform the most important parameters that influence ROI, such as electricity pricing. The KB and database aim to fill the gaps in knowledge, as well as providing relevant case-studies for selections made. Once the decision-maker has finalised their farm (or it has already been built), they can use the DSS with their farm data to drive operational improvements, find methods to increase profitability and become scalable.

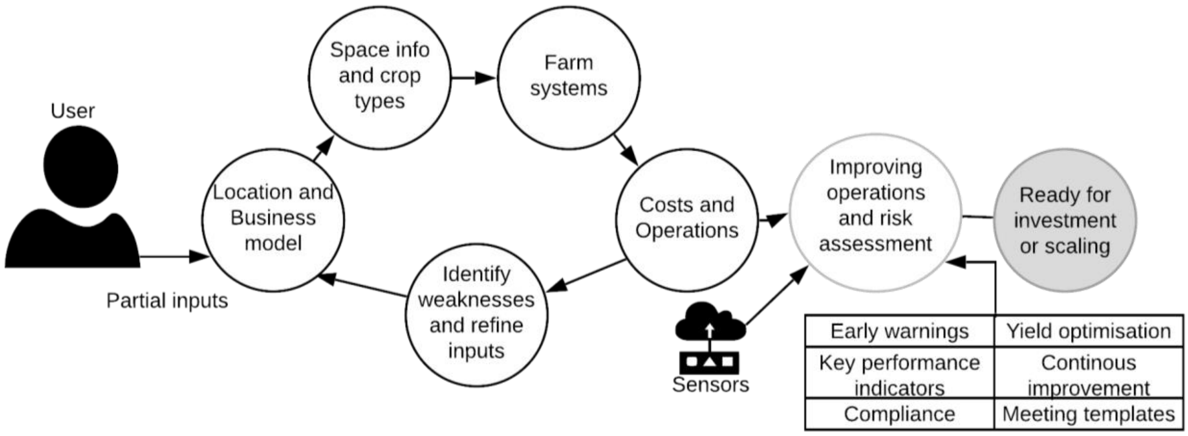

Figure 3.8. The user flow of the DSS aims to bring the decision-makers to a profitable business model through several iteration cycles before providing steps to improve operational efficiency and performance when using real farm data.

The database, KB, ML and UI, -and how they interact - must be clearly defined to design a useful system. Poorly designed software may result in complex interfaces, unnecessary development and time-consuming simulations which often hinder their use [272]. Figure 3.9 shows the system process structure of the proposed DSS, which has been adapted from the economic estimation tool "VFer" [76]. The adapted structure includes additional steps to improve accuracy, adaptability and include risk and uncertainty. The flow can be followed starting from the top to the bottom.

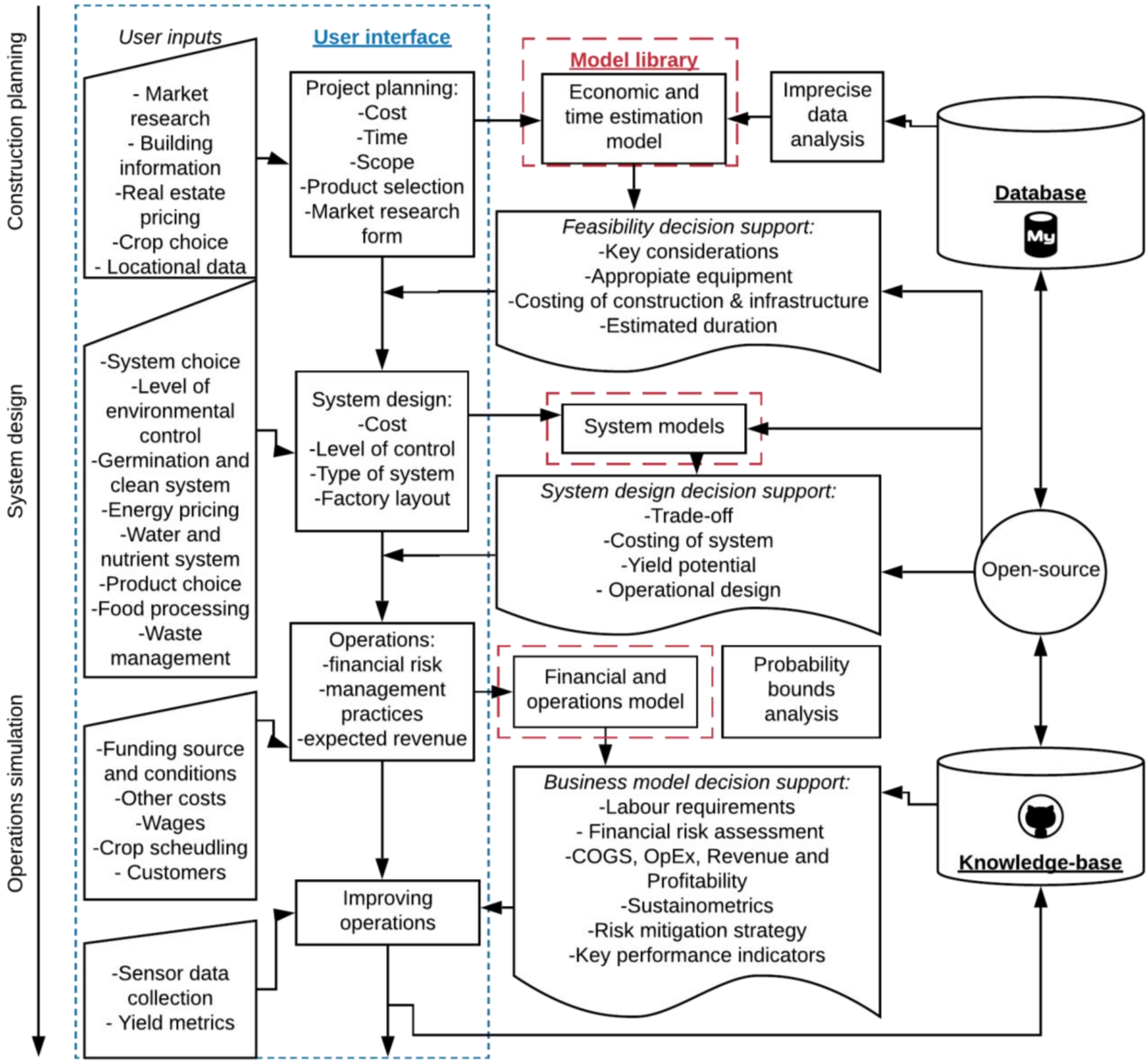

Figure 3.9. System processing structure for the DSS (cf. [76])

The DSS framework requires only partial information, and highlights gaps where evidence is required. Missing entries are filled with assumptions from the KB and database where possible. The DSS is intended to be a deep-learning tool that enables the users to collate all their information within the same place and provides guidance at an early conceptual stage of development. This can greatly benefit decision-makers to see the impact of business decisions or farm decisions. The users are provided the opportunity to apply and evaluate different courses of action due to the imprecise techniques applied, as well as iterate their business decisions towards profitability. As the users acquire more information about their parameters, they can improve their precision and identify key decisions for higher ROI. According to the constructivist approach, such models are useful constructs to generate reflections on the part of the decision-maker, helping them to build knowledge through this learner-simulation and to make evidence-based judgements [273,274].

3.6.2 The Database

The database is where necessary datasets are stored to be utilised in the DSS's processes. Data is sourced from available literature and the interviews conducted using the elicitation protocol for VF practitioners, both in industry and academia. The datasets are then stored online using MySQL, an open-source database platform. This is to promote the intention of a standardised open platform that enables users to share their data through cross-licensing. Cross-licensing ensures protection of intellectual property of other parties. VF lends itself well to this open data approach for crop data specifically, since commercial indoor VF is conducted in nearly airtight and thermally well insulated facilities [80]. Inputs, outputs, waste and resource-use efficiency can be continuously measured online, and standardisation of data collection can inform a better understanding of interaction of plants with environments and machines. This open sourcing across farms and business produces a growing bank of useful knowledge for stronger businesses that can minimise risk, resources and challenges [80]. The architecture for the database is illustrated in Figure 3.10. Manual inputs, sensors and processing nodes are integrated to provide environmental information (humidity, temperature, nutrient levels, CO_2 and more).

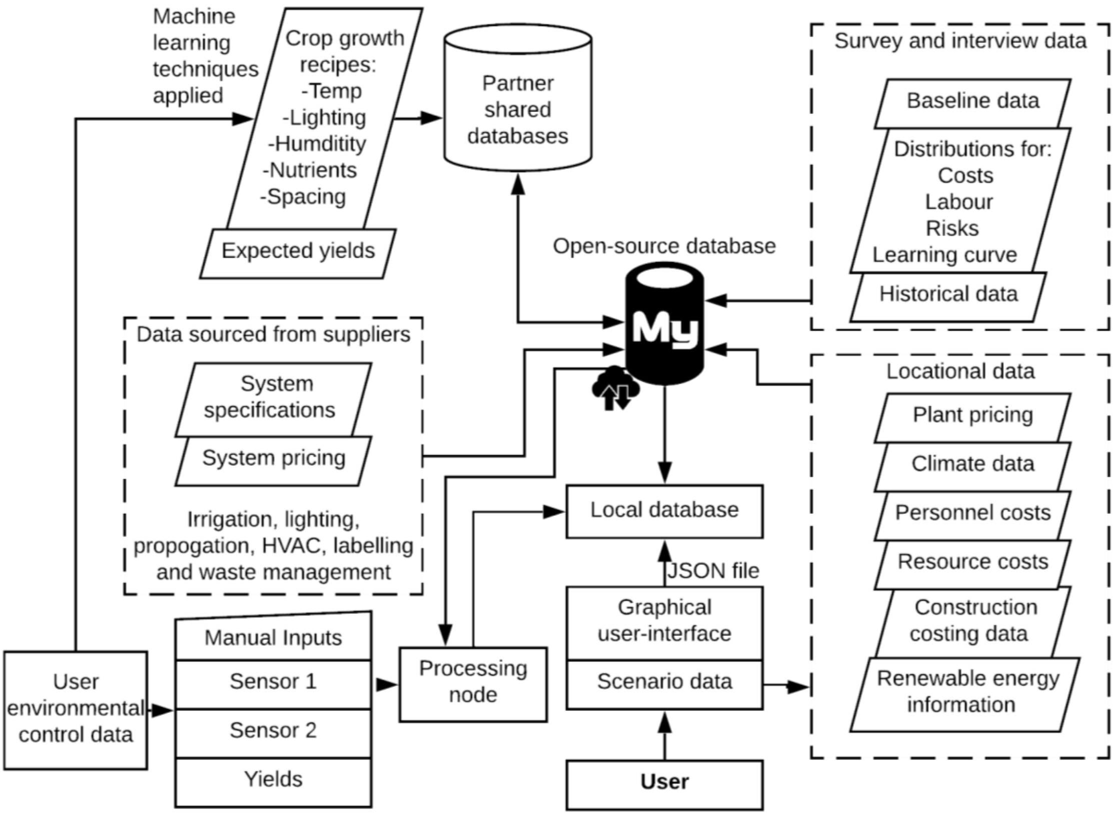

Figure 3.10. The DSS distributed architecture for database management with a core MySQL open-source database

Shared user-data allows the validation and correction of models contained in the ML. Time-consuming locational data can be shared to reduce the effort required for future projects, as well as adding new findings (such as lighting solutions, farm systems and plant recipes). For initial construction costing data and information on crop requirements, see paper on VFer [76]. Establishing baseline data for productivity metrics is equally important [275] to drive forward innovation towards sustainability. By developing a database through an open-source approach, the DSS becomes smarter continuously. With the capability to self-learn and continuously update, the DSS classifies as intelligent [276]. Transparency and collaboration are encouraged to reduce mistakes for all users in this complex field. With an open-source license, it will have permission to call upon other potential open-source databases, similar to crowdsourced OpenAg project [265] which applied machine learning techniques to optimise plant growth, flavour and nutrients. Although this project is now on hold, it may re-emerge. For others with valuable and hard-earned proprietary data and algorithms, they may be reluctant to share their competitive edge. This is understandable and charging users for access to add-on modules with cross-licensing is a potential option to benefit those concerned parties.

3.6.3 The Knowledge Base

The open-source KB utilises a wiki engine embedded into the DSS framework. It can be accessed standalone, decentralising knowledge sharing whilst promoting greater collaboration, transparency and accelerated knowledge exchange. A Git repository is used via GITHUB for distributed version control and can be found at https://github.com/GaiaKnowledge/VerticalFarming. The KB is either accessible through a web-browser or linked directly through the DSS, acting as a help or additional information menu. It attempts to crowdsource research and best practices for the vertical farming industry, which due to lack of standardisation or guidelines, has been identified as a key bottleneck to industry progression [79].

The KB includes processes, operational procedures, best management practices, fault tree diagrams, document templates, food safety management standards (ISO22000 and hazard analysis and critical control point (HACCP)), risk management guidelines, information on technology solutions and more. Figure 3.11 shows the KB architecture, the sources of knowledge (including the user) and the various categories of knowledge that have been identified for the system. Much of this information is sourced from existing literature and the data collection methodology described within this paper. A key component is a risk register gathered from challenges experienced by study participants and anecdotal evidence (see also [71,78,242]. Knowledge can be used to acquire strategies to deal with common problems such as certain diseases or pests and would avoid users searching through scattered literature or seeking expert knowledge.

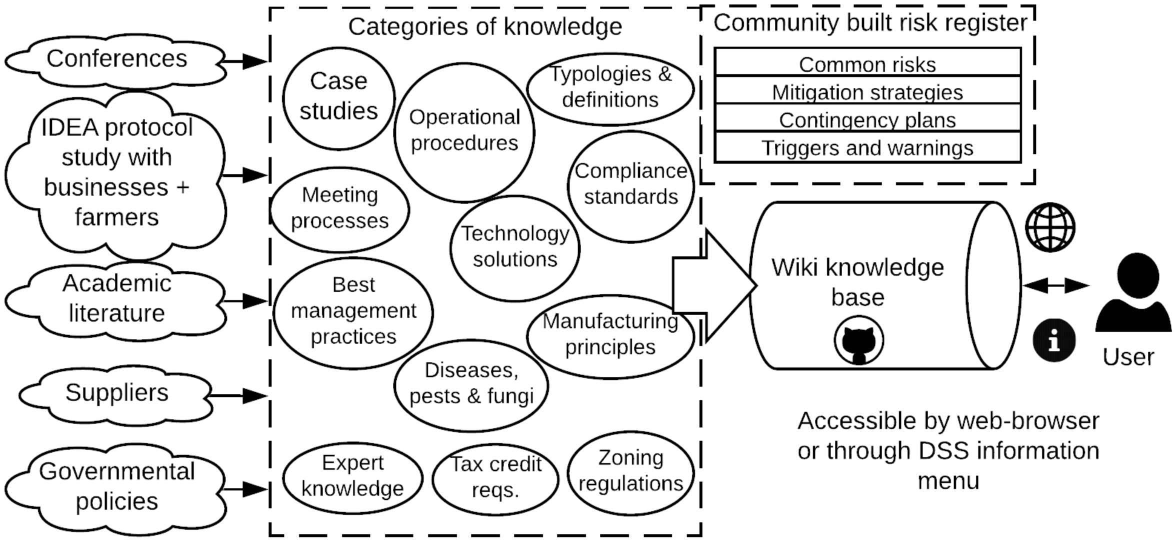

Figure 3.11. Knowledge base wiki-structure with categories of information discovered in an open-source repository.

3.6.4 THE MODEL LIBRARY

The ML embedded within the DSS is held within the same open-source Git repository in development as the KB (accessed via https://github.com/GaiaKnowledge/VerticalFarming). The general-purpose programming language Python will be used for the analyses contained within the ML. This decision is justified because Python is free to use, suited to modular projects, has an extensive set of libraries for analysis of data, sensor connectivity and machine learning. The ML structure is broken down into several steps illustrated in Figure 3.12. The core set of models are part of the financial toolkit described as the ROI and profitability models in Section 3.5. Technical optimisation, as established in the literature review, is currently being addressed by other software developments and therefore specifics have been omitted. Technical optimisation would link well to the DSS as solutions begin to converge as is being seen recently.

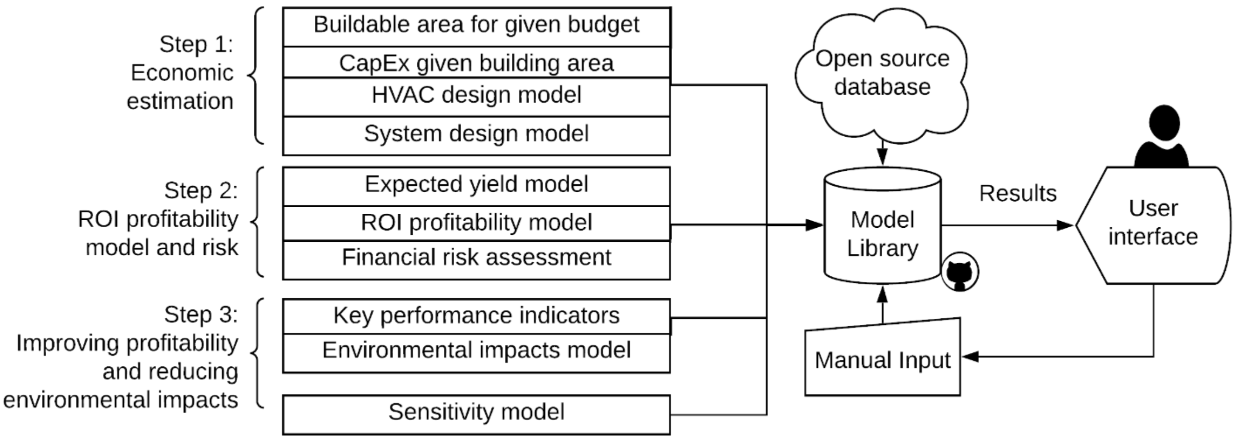

Figure 3.12. The ML structure is broken into three steps.

3.6.5 THE USER INTERFACE

The UI enables users to interact with the DSS through a web browser to improve accessibility amongst several users, as vertical farms typically involve several stakeholders that need to review decisions. Development of a graphical user interface (GUI) will ensure end users (managers and VF project teams) are able to interact with the DSS intuitively and display results meaningfully. The GUI could be developed using a framework for object-orientated web systems in Python language (i.e. Django or Flask). A mock-up GUI is illustrated using a vertical farm in Liverpool as a case study. This will be used in the interview studies to gather feedback to ensure the system is holistically designed to meet end-users needs. The mock-ups are discussed within this section to describe the functionality of the proposed DSS and how they fill the research gaps identified.

Farm Project Planning:

To build a scenario the user opens the project planning tab and proceeds to input details for:

1. location and building characteristics (see Figure 3.13),
2. market and business model,
3. infrastructure,
4. product and pricing (see Figure 3.14),
5. funding.

Inputs are saved in a JSON format to be interpreted and analysed within the ML.

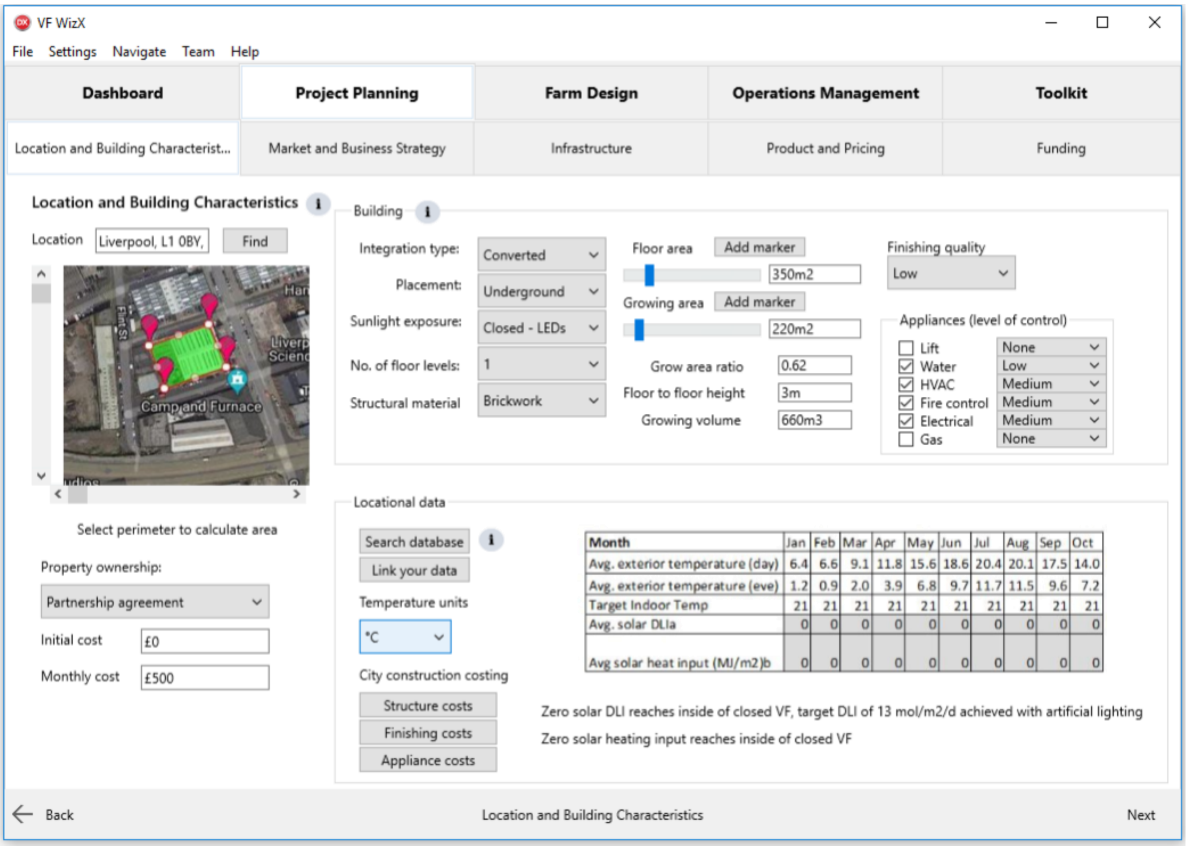

Figure 3.13. Window for project planning: building and location user inputs of the DSS, Map data from ©2019 Google [277]

The database provides a catalogue of crops to choose from, and their typical prices for the country of use (see also [76]) for information regarding crop pricing and requirements. Tooltips give decision support to alert the users that certain crops may or may not align well with a specified location, size or business model (e.g. high-value niche products are suitable for smaller facilities serving restaurants and vine crops should not be grown with solely artificial lighting). The user can select a best-case and worst-case scenario to evaluate their revenue streams when inserting uncertain values defined by the parameter editor.

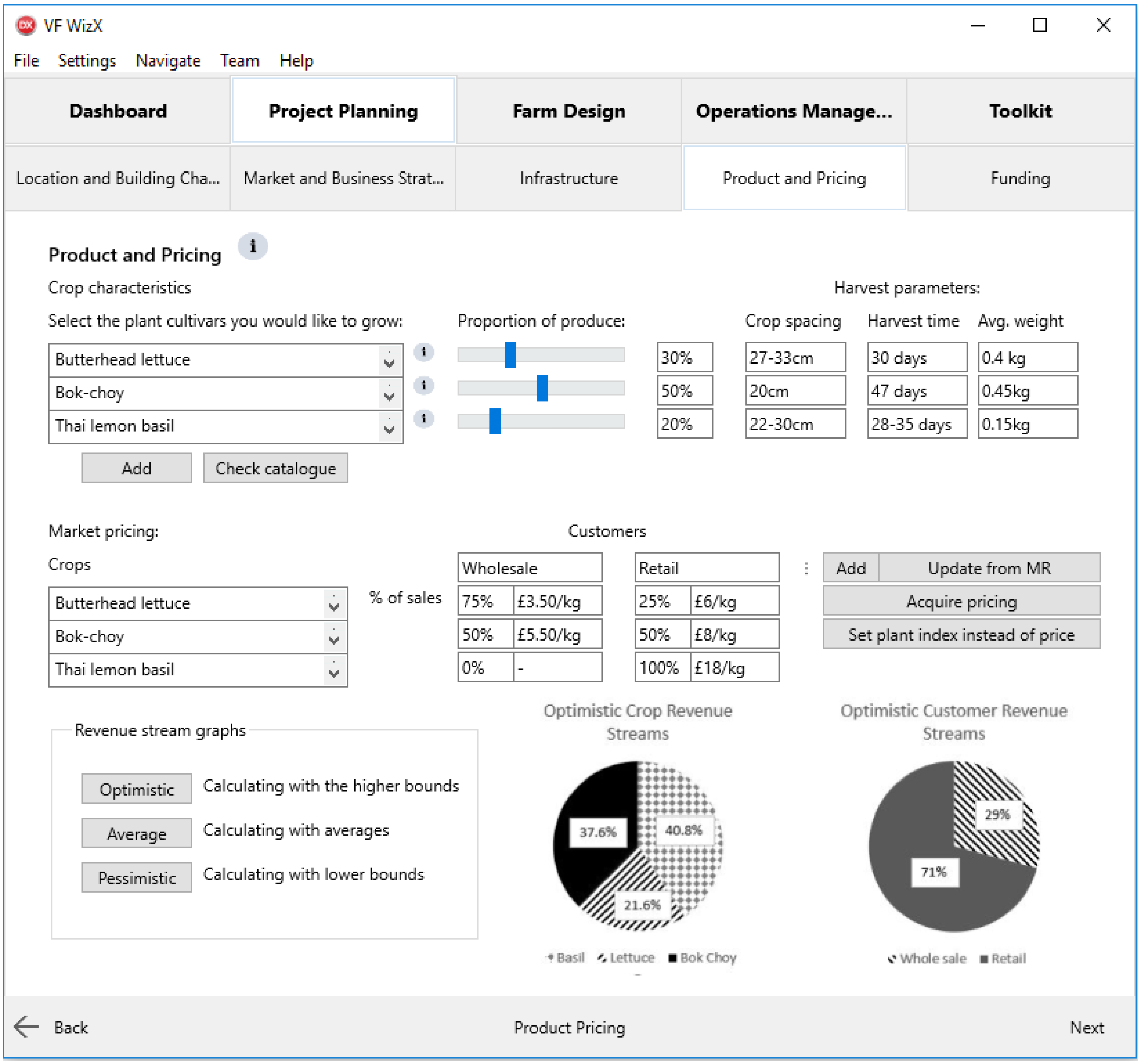

Figure 3.14. Window for project planning: product selection and pricing

Parameter Editor:

Although fields will be prepopulated where possible, an integral part to the DSS is the parameter editor interface (see Figure 3.15). It can be opened by double-clicking any field and can self-document any changes the user makes. It accepts linguistic inputs as fuzzy logic [274] to improve usability. The units can be defined complimented by magnitudes that can be imprecise (with statistical data provided if available). The nature of the value, its justification and any supporting data or documentation can be attached. The intention is that multiple users can access the system and understand the decision-making process behind existing judgements. A field is highlighted red in the main windows if no justification has been provided.

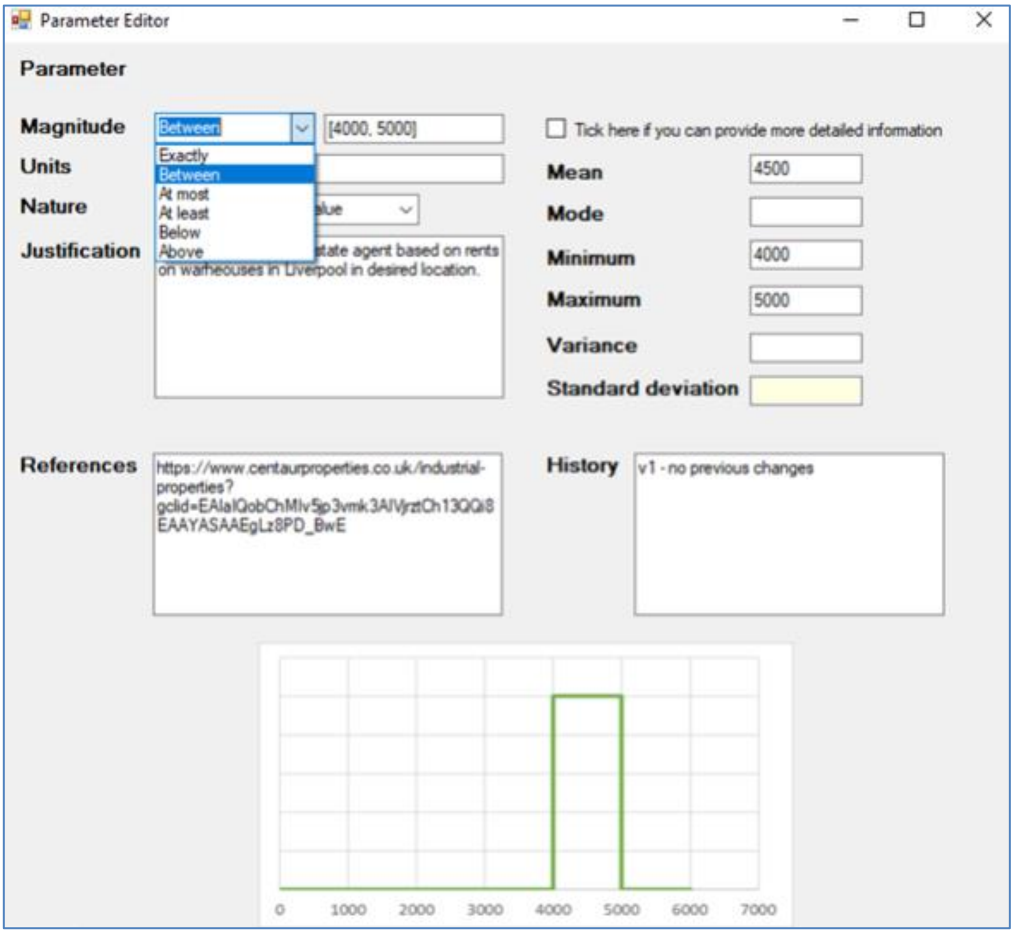

Figure 3.15. Parameter editor that allows self-documentation for any field

<u>Farm Systems Design:</u>

The farm design menu allows the user to select and design for:

1. irrigation,
2. HVAC,
3. lighting (depicted in Figure 3.16),
4. floor layouts,
5. other technology choices.

Various lighting solutions can be picked from the database lighting catalogue, or the user can insert their own. Currently the grow light industry is unregulated, and the specifications given by suppliers are not standardised. The mock-up of the lighting window will be used to consult with lighting suppliers and design a window which fit for purpose, encouraging standardisation. The catalogue will have the relevant details and be able to match spectrum to associated crops for different environments.

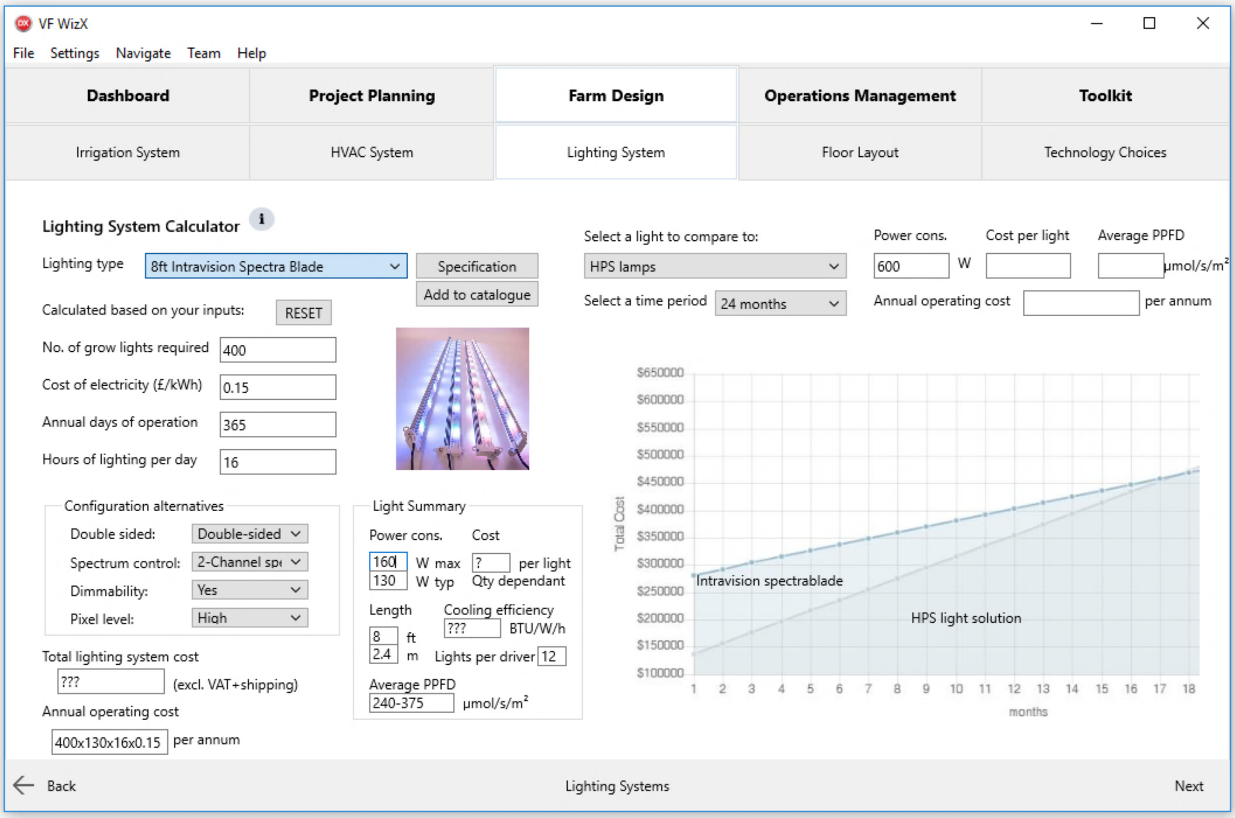

Figure 3.16. Window for farm design: lighting systems for selecting and comparing lighting solutions ©2019 Intravision [268]. Used with permission.

Operations Management:

The operations menu has the following tabs:

1. labour management
2. crop scheduling
3. management practices
4. resource management
5. distribution and sales
6. utilities management (energy performance is depicted in Figure 3.17)
7. sensor integration

Default values depending on sizing are given for number of hours associated with labour costs for a farm. Decision support can tell users exactly what data they should collect to encourage standardisation and collaboration, a pre-requisite for machine learning. The DSS can model the electricity performance of the user's farm compared to targets set by the user or recommendations from the database. ROI is highly dependent on electricity pricing [76] and therefore it is important to encourage measures to reduce this cost.

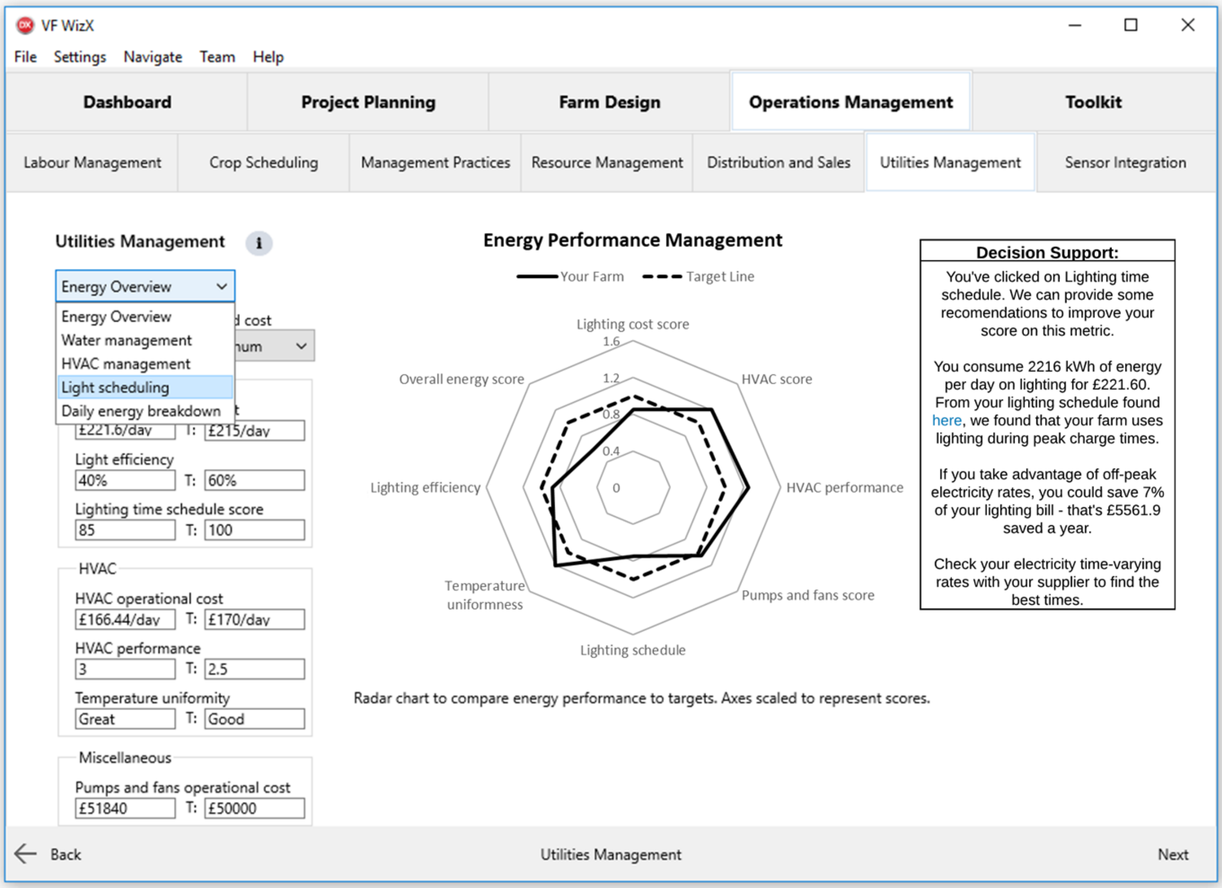

Figure 3.17. Utility management window (cf. [263])

Toolkit:

The toolkit menu contains the following tabs:

1. feasibility
2. business model and ROI
3. ROI risk assessment
4. risk management (see Figure 3.18 for risk register [278,279]
5. productivity metrics (see Figure 3.19 for sustainability metrics proposed by [275,280]).
6. team management

Reports can be prepared from the user's entries and after simulations have been run. The reports can be used for urban planners and financial investors to communicate complex information about financial risk and building requirements. The risk management strategy helps teams to prevent knee-jerk reactions to unforeseen problems. This process cultivates an informed culture in which management and operators are knowledgeable about factors that influence safety and reliability of systems [278]. A built-in meeting scheduler is used to promote group decision-making processes (see [252]) with templates such as the five-whys root-cause analysis (see [281]) sourced from the KB.

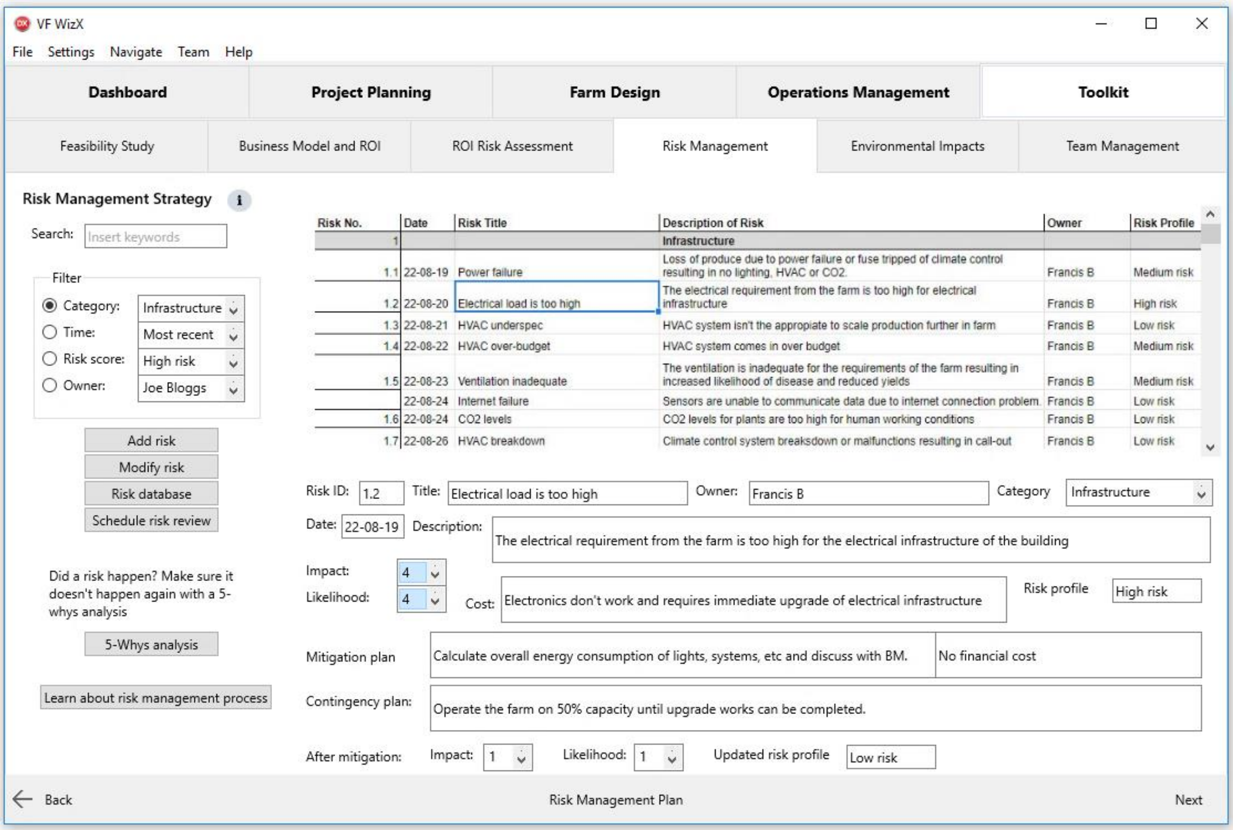

Figure 3.18. Risk management window within the toolkit tab of the DSS.

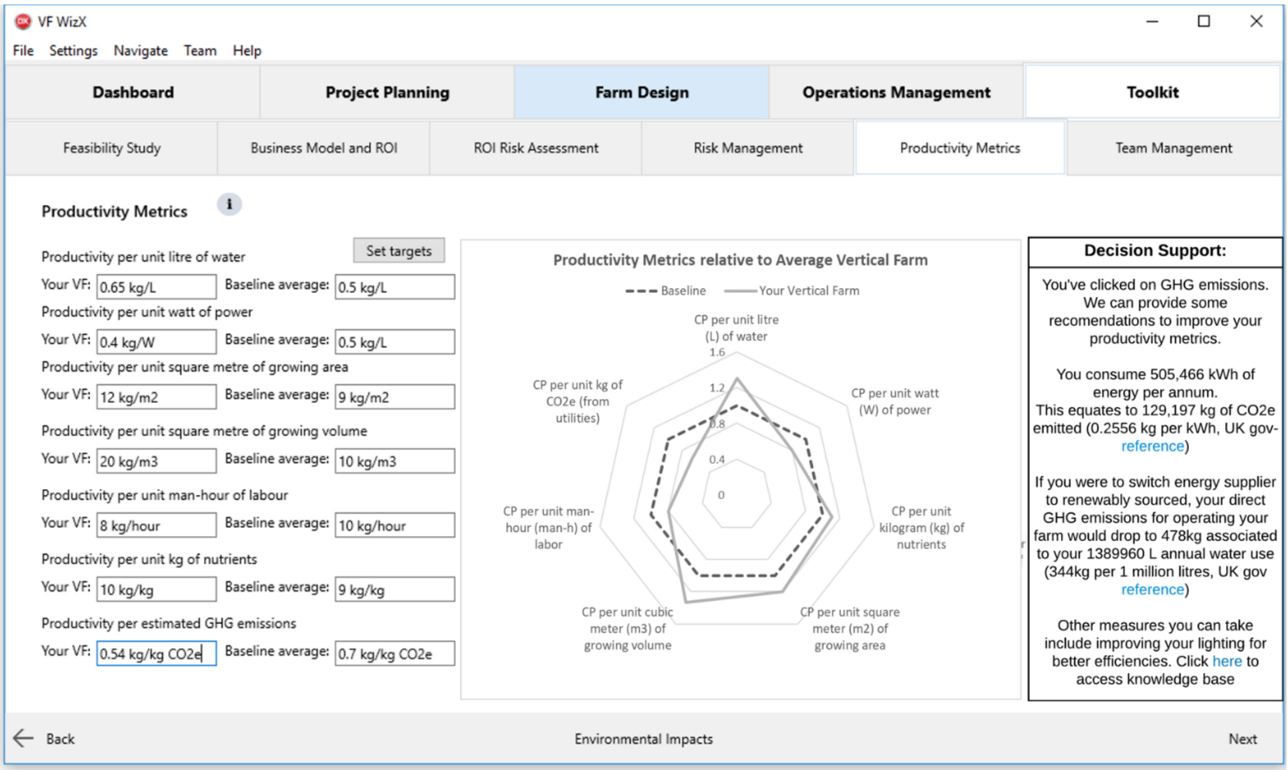

Figure 3.19. Sustainability-based productivity metrics window (cf. [275]).

3.7 CONCLUSIONS

The vertical farming (VF) industry will gain further traction in the next few years due to the strong market drivers from global challenges and maturing technology. Despite increasing investment from venture capitalists and large investment rounds from those who see potential to disrupt the leafy-green, salad and herb market, the path to profitable and scalable business models is not obvious. To ensure profitability, a deep, comparative and scientific economic analysis is required. This analysis must incorporate the effects of the learning curve and risks and uncertainty to accurately forecast finances for entrepreneurs. Collaboration, rapid improvements in light-emitting diode efficiency over the next several years, and higher price-points for VF crops have been identified as drivers for increasing profitability to desired levels of return on investment for investors and farm owners. The decision support system (DSS) framework proposed here aims to aid users with business sustainability and risk-empowered business plans. Decision-makers can avoid costly mistakes early on in projects by having a clear method to their business planning, testing various scenarios by only requiring partial inputs for feasibility assessments. The planning and development processes constitute a multi-complex problem that is difficult to solve if not addressed thoroughly. The interdependence between production activities and post-production services is high, making planning challenging. Making decisions to develop a vertical farm is influenced by many factors and is not based on simple and well-defined rules, but rather the knowledge, skills and experience of the decision-makers. This DSS framework evaluates the information provided by the decision-makers and supplements it with the database and knowledge base to deliver an economic analysis supplemented with advice to meet key performance indicator targets.

The system utilises open-source architecture for the knowledge-base, database and model library to crowdsource research and collate scattered information. Development of the DSS and supporting data collection is underway, alongside the building of a wiki for lessons learned and operational processes (accessed via https://github.com/GaiaKnowledge/VerticalFarming). There are many challenges it seeks to address: (i) the inherent learning curve when estimating yields, (ii) reliable and flexible economic analysis with scarce data, (iii) risk assessment, (iv) project risk management, (v) tracking of sustainability-based productivity metrics, (vi) centralisation of equipment specifications, (vii) simplification of data collection, (viii) decision support for operational improvements, (ix) guidance on reducing environmental impacts, (x) crop requirements and (xi) informing decision-makers on best management practices.

The DSS framework can benefit decision-makers by providing expert knowledge that reduces costly and time-consuming research and development. It can ensure businesses allocate effort in the processes of the farm that add the most value and drive higher profit margins. By sharing knowledge across the sector, the DSS can highlight the route to profitability, inform collaborative business models and use the reporting features to assure risk-averse developers or investors or viable pay-back periods. Standardising the design and management of vertical farms is needed in order to earn recognition of this new urban building typology. This is vital as very few countries have adapted policy to include zoning use of agriculture in cities and financers do not know how to include lighting and equipment as assets. Most importantly, the DSS aims to reduce a VF business' uncertainty.

In order to realise this DSS framework, a rapid-prototyping methodology has been adopted to gather end-user feedback on the graphical user interface mock-ups and core financial risk assessment component of the DSS. The framework is being developed empirically alongside a UK-based VF enterprise. This system is at the conceptual stage, constructed based on a combination of research gleaned from gaps in literature and systemic thinking around possible best fit approaches to tackle the key challenges related to VF business development from a software design perspective. As a further step in the development of the research the authors recognize the need for model's robust validation as a pilot for performance gaps closure and continuous improvement. The conceptual design stage is often limited by relevant design date, hence at this early stage the use of assumption based approaches are necessary to inform default values/criteria [282]. Furthermore, only at the software testing stage will the authors be better positioned to validate and inform future direction as part of the early stage of this applications lifecycle. Hence, prior to any "live" delivery the system requires a viable minimum functional requirements strategy as evidenced in the discourse allowing contributions of other academic and industry partners to contribute though feedback [283]. The DSS development requires expertise for software development, lighting systems, building climate control, plant physiology, urban planning, energy management, engineering, nutrient dosing and more. Future work will entail bringing together a consortium of partners and drawing upon contributors to collaborate on the open-source wiki-base, models and database. Consortium building is currently underway.

CHAPTER 4

QUALITATIVE INTERVIEW STUDY

FRAMING

In Chapter 3, the expert elicitation protocol (IDEA protocol) [266] was presented to conduct interviews and observations with VPF operators and associated businesses to inform the DSS development. The goal was to collect data that would inform the DSS and collect benchmarking metrics of economics, risk quantification, and yields. This was attempted for a 3-year period. Unfortunately, several unforeseen obstacles throughout the PhD project changed the course of the proposed study, which forced the analysis to be adapted:

- The pre-competitive environment in the sector led to low uptake from operators on invitations and advertisements;
- The ethical approval documentation which interviewees found disconcerting and therefore did not participate;
- The operators' lack of time, quiet space, and data collection to complete online surveys and interviews at the required pace;
- The discomfort from participants to provide upper, lower, and best estimates for uncertain parameters following the three and four-step protocols (despite initial training);
- The COVID-19 pandemic led to interviews and exercises being conducted over virtual platforms; and
- The limited data set was insufficient to aggregate data into classifications proposed in Chapter 2.

The study was intended to provide quantitative results; however, the outcome was more qualitatively focused and was still successful focus. Semi-structured research interviews and site visits were conducted worldwide with operators, vendors, consultants and researchers. After 20 interviews, the qualitative data reached a level of saturation, and no additional findings were being generated. A mixed-methods approach using reflexive thematic analysis was applied to the data for lessons learned, recorded risks, failure modes, and guidelines which can be used within the knowledge base of the DSS depending on the VPF configuration and business model. From this experience, I conclude that the academic approach to uncertainty quantification based on the IDEA protocol may not be suited for industry practitioners instead of academic experts. Further investigation of expert elicitation protocols for risk assessment in industry contexts is required. Ethical approval for the study can be found in Appendix E.

This study is in press to be published as a book chapter *in Plant Factories: New Technologies in Indoor Vertical Farming*, Editors Prof Toyoki Kozai and Dr Eri Hayashi, as "Lessons Learned from Existing and Shuttered Vertical Plant Farms". The book chapter will be published by Burleigh Dodds Science Publishing and was granted permission to be included in this thesis. The original chapter can be accessed at https://www.bdspublishing.com/. In addition, the article underwent peer review by the editors.

The contributions of the authors are the following: F.B.D.O conceptualised the research idea, F.B.D.O. designed the methodology, F.B.D.O. sought ethical approval, F.B.D.O. designed the surveys and interview questions, F.B.D.O. conducted interviews, F.B.D.O. conducted site-visits, F.B.D.O. transcribed the interviews, F.B.D.O. analysed the data, F.B.D.O. wrote the paper, F.B.D.O. reviewed and edited the paper, R.D. supervised.

Ronald Dyer individually consented to the use of this publication within this thesis.

LESSONS LEARNED FROM EXISTING AND SHUTTERED VERTICAL PLANT FARMS

Advances in Plant Factories: New Technologies in Indoor Vertical Farming, 2023

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4.1 ABSTRACT

Vertical plant farming (VPF), defined as crop production utilising vertical space through stacking horizontally or in towers, is a promising and relatively novel type of controlled environment agriculture (CEA). The nascent sector has been riddled with complexities in economic viability, labour, and plant science, evidenced by a landscape littered with failed start-ups. No studies have examined lessons learned from vertical plant farms. We analyse the interviews of 20 industry practitioners growing leafy vegetables, microgreens, herbs and edible flowers. We examine the experiences of both profitable farms and shuttered projects and their reasons for closure. Thematic analysis is used to identify lessons learned. The lessons fall under six themes: i) economics, ii) labour, iii) technology, iv) growing, v) strategy, and viii) risk. We explore these themes to provide guidelines for successful VPF projects grounded in the literature. This discourse includes a risk register comprised of all reported risks affecting VPF.

4.2 INTRODUCTION

Within this chapter, a plant factory or vertical plant farm is defined as an operation that cultivates plants using vertical space in a controlled environment. Plants can be stacked on top of each other using multi-tier racking or vertical towers and can be grown with natural or artificial lighting. When a vertical plant farm specifically grows plants without sunlight, it is categorised as an indoor vertical farm (IVF) or plant factory with artificial lighting (PFAL). These terms will be used interchangeably. Typically, a vertical plant farm uses soilless hydroponic techniques. This study predominantly focuses on IVFs with a couple of exceptions and all of the farms utilised hydroponic techniques. The benefits of utilising these techniques are explored elsewhere in this book.

Recent advances in light-emitting diode (LED), automation and greenhouse technologies have catalysed the VPF industry [19]. Deep expertise is required to reverse-engineer nature's processes to achieve optimal results in a controlled environment. The practice is still in its innovative stages, and many VPF companies have been developing farm technology whilst operating their farms. The risk and investment required mean there has been some secrecy around business models and lessons learned [77]. Some insiders complain that vertical farming is mostly "smoke and mirrors" [72,180], implying the route to business viability may not be as clear cut as first appears.

VPF has reached an inflexion point where industry operations begin to scale and strive for positive unit economics. However, banks and traditional investors highlight their cautious optimism and hesitancy to invest in this high-risk sector [83]. In addition, a lack of benchmarking data, best practices and proven business models are barriers to access to funding [83]. These factors reflect a prominent industry survey that found the top reported challenges in the sector were labour, raising funding, and scaling [61].

Since the accelerated development of commercial vertical plant farms in 2010, many farms have shut down. Although there is no official record of the number of shuttered farms, the failure rate is thought to be high. In addition, high operational costs and complexity will probably result in more costly failures to come. Figure 4.1 shows several examples of projects that have not survived due to reasons explored later in this discourse.

Figure 4.1. Shuttered vertical plant farm projects a) Local Garden [284], b) FarmedHere [285], c) Wigan UTC [286]. Used with written permission.

There is no data on what drives operations to close but only anecdotal reports, which will be examined more closely in Section 3. As a new sector, there are unknown risk factors that the literature is yet to explore, and therefore entrepreneurs are left to speculate what the risks may be. This issue is amplified by a lack of experience, with 49% of entrants having no agricultural experience [42]. Additionally, there is no standard method for building vertical farms, and there is a wide diversity of designs and practices. On the other side of the spectrum, there are profitable farms but the core factors driving their success have yet to be explored. Figure 4.2 shows two operational and profitable IVF operations.

Figure 4.2. Profitable indoor vertical farm projects a) 808 Factory [149], b) greenLand [154]. Used with permission.

Identifying lessons learned as a post-project review system can help improve performance, reduce effort, and prevent the repetition of similar mistakes [287]. This review system has been applied in many industries, including agriculture [288]. It is relevant to vertical farming because of three aspects:

- the unprecedented regulatory territory of urban food-water-energy projects;
- the high failure rate; and
- the lack of proven business models that are capable of scalability.

We aim to derive lessons from VPF start-ups for best practices. We will do this through reflexive thematic analysis applied to a series of interviews and secondary data items [289,290]. The objectives are as follows:

1. review related works and anecdotal learning experiences of building and operating vertical farms;
2. identify thought-leaders viewpoints on aspects that have aided or hindered vertical farming's emergence;
3. use a taxonomical hierarchy to categorise viewpoints into core themes;
4. identify specific lessons learned by themes;
5. identify failure modes of vertical farms; and
6. develop guidelines to support vertical farms.

There has been no formal literature examining lessons learned from vertical plant farming (VPF) projects, although there are discussions for greenhouses with some cross-applicability [291,292]. Discussions of lessons from VPF have been exchanged in blog posts, online videos, and industry conferences [73,78,200,293], but there has been no academic analysis. In this research, we integrate findings from both the formal and informal literature to inform an initial thematic taxonomy (see Figure 4.3).

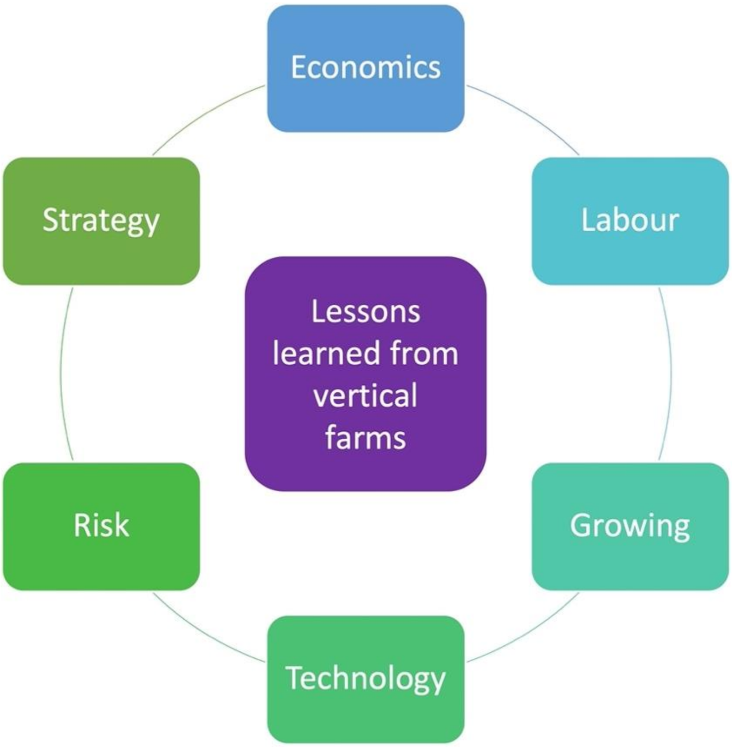

Figure 4.3. Initial thematic taxonomy based on related work.

4.3 Methodology

This study uses a mixed-method reflexive thematic analysis (TA) drawing from Braun and Clarke [289]. Reflexive TA is an open-ended approach that facilitates identifying and analysing patterns (themes) within data [294]. We adopted an inductive approach as we code mainly from the data and draw upon some existing concepts from the primary researcher's knowledge. The focus of this study is experiential and exploratory, giving voice to the experiences of the practitioners (interviewees) of vertical farming businesses.

Interviews occurred either at the participant's place of work or through online video calls. Interviews were semi-structured. We employed a purposeful sampling strategy [295] by selecting a combination of farm operators, business owners (of both closed and operating farms), vendors, and consultants that have helped set up multiple vertical farms. Overall, we recruited 20 participants across 18 companies for this study. In addition, 10 secondary sources were used within the analysis to account for other shuttered farm operators' and practitioners' experiences [73,78,180,200,293,296–300]. Figure 4.4 and Table 4.1 show the sample population characteristics including relevant secondary sources.

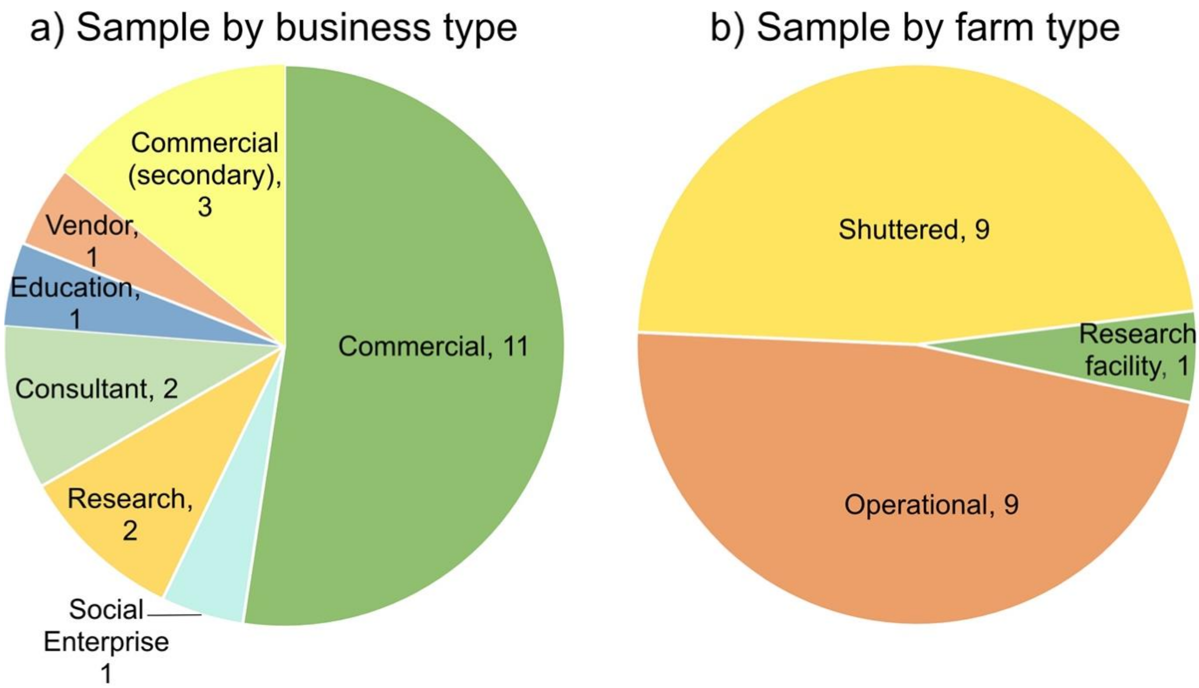

Figure 4.4. Sample characteristics for 21 businesses and 19 farms.

Table 4.1. Population information for farms

Characteristic	Data
Notable crop types:	Leafy vegetables: lettuce, chard, kale, spinach, rocket, salad mix, cabbages, mizuna, and mustard greens. Herbs: basil, coriander, thyme, mint, dill, and parsley. Microgreens: pea sprouts, cabbages, sunflower sprouts, coriander, basil, broccoli, brassicas, amaranth, wheatgrass, cress, kale, and radish. Edible flowers: nasturtiums, pansies, and violas.
Production quantity	Between 260-584,000 kg/year, mean: 173,000 kg/year, standard deviation: 229,000 kg/year
Facility farm size	Between 20-10,000 m^2, mean: 1680 m^2, standard deviation: 3140 m^2
Farm launch year	Between 2008-2020, mode: 2018
Company lifespan	Between 1-10 years. Mean: 4.71 years
Configurations	Greenhouse vertical farm (10.5%), indoor vertical farm (63.2%), container (15.8%), façade vertical farm (10.5%) and multi-floor farm (15.7%)
Irrigation systems (for definitions see [18,127]).	Vertical growing towers (5-foot and 8-foot, ZipGrow™ towers [187]) Nutrient film technique (NFT) racks (bespoke and 5-layer racks from V-Farm™ [301]. Deep flow technique (DFT) racks (bespoke) Ebb and flow systems (bespoke), Aeroponic spray system (bespoke) Modified hybrid NFT/DFT system
Locations	United Kingdom, France, United States of America, Sweden, Denmark, Canada, Australia, Japan
Profitability of commercial farms	10.5% profitable, 89.5% unprofitable

4.4 Results

This section presents the analysed results of reflexive TA from coding 20 interview transcripts alongside 10 news articles, blog posts, and conference panels. The six subsections address the themes and sub-themes generated from the data with analysis grounded in the literature.

4.4.1 THEME 1: ECONOMICS

The economics of VPF is a central element explored within the interviews. There is substantial uncertainty about the economics of VPF due to a lack of peer-reviewed and real-life production or financial data available on a commercial scale [75,82]. This section highlights participants' path towards economic viability, capital funding, and cost components (see sub-themes illustrated in Figure 4.5 with percentage of occurrence within the dataset).

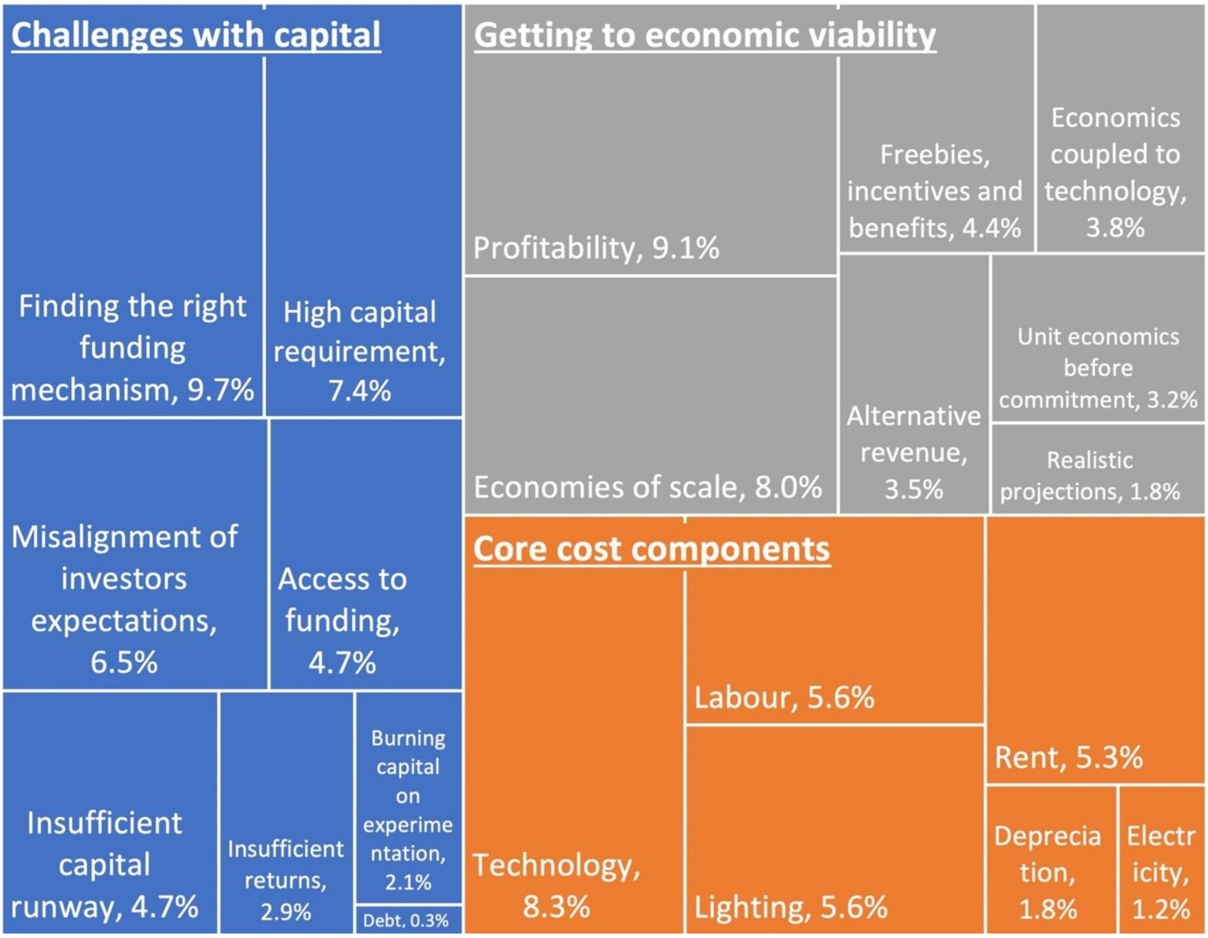

Figure 4.5. Economics sub-themes and codes.

Getting to economic viability

Economic viability is critical for vertical farms to expand globally and improve consumer access through affordability. Two of the nineteen farms considered in this sample were profitable. This reflects the difficulty in developing financially sustainable farms. Although indoor vertical farms can be economically viable [42,82,115] there are no business models that have demonstrated scalability at the time of writing this chapter. Rising electricity prices and inflation across the globe after the coronavirus pandemic and Russia's invasion of Ukraine will have no doubt influenced the delayed scaling of companies in the VPF sector.

Many farms struggled with financial forecasting as there was too much uncertainty in the early stages to accurately predict their return on investment (see Section 4.4.4 for further detail). Several farm operators underlined that alternative revenue buffered their farm operations so that they were not solely reliant on sales to be viable. Successful farm owners were able to benefit from consulting to leverage their expertise, which paid for research and development costs. It was also clear from responses that the economic viability of VPF is closely tied to technology selection. There were mixed responses about whether technology was currently economically viable (see Section 4.4.4). However, two profitable PFALs revealed that they reached their break-even point within 2-3 years of operation. They attributed this to high productivity, strict management costs (their core management team was small and competent), and a strong customer focus (solving a problem for their customer and marketing).

From the perspective of economies of scale, operating smaller farms and larger farms have different trade-offs depending on their customers. Operators and consultants reported that a viable farm targeting wholesale customers should have a minimum footprint of 1000 m^2 and up to 6000 m^2 and focus on a small number of crops. One profitable and long-standing PFAL operator revealed that multiple modularised growing rooms of 500 m^2 provided the best labour efficiency and ease of maintenance, which can then be scaled by adding adjacent growing rooms. A growing module has the primary benefit of having systems serviced without comprising the entire farm to pests or hygiene issues. Beyond 500 m^2, operators experienced diminishing benefits of labour efficiency due to excess movement. This modularised approach supports the discussion of cultivation module systems in other literature as well as the latest industry trends [302]. On the other hand, smaller farms can produce a wider variety of crops and target retail customers. It was affirmed that a size between 50 m^2 and 200 m^2 was suitable for smaller farms. Locations for respective farm types are discussed in Section 4.4.5.

32% of farm operators discussed their experience benefiting from subsidised rent, capital costs, or electricity and how it was vital to sustaining their business. In these cases, farms report being able to negotiate free rent and subsidised utilities by providing added value to a location. Moreover, farms can benefit from strategic placement next to a power plant to uptake excess energy. Some regional governments may support this with subsidies (this was the case for one Japanese farm). Location partnerships were the primary reason several small farms reported that they could function economically long-term, however, one operator achieved profitability without any subsidies or incentives.

Challenges with financing

Challenges with capital were the most discussed aspect of economics, which is expected considering the high costs required to build and operate vertical farms. In recent industry surveys, CEA owners' most commonly reported issue was funding and 71% of founders were either unsuccessful in raising capital or could not rely on traditional sources like commercial lenders for financing [42,61]. Within the interviews, farm owners discussed access to funding, accumulating debt and burning capital on experimentation.

The growing system and lighting technology required to build and operate a vertical farm are notoriously expensive, and this was the most common complaint across all the interviews. Operators reported that when they paid less upfront (CapEx), they ended up having higher costs to run the business (OpEx) [297]. This high capital requirement for economic viability is a considerable challenge, as practitioners' complained that access to funding is their primary barrier to growth. This is due to a lack of proven business models and benchmarking data as well as numerous failures which have made investors and bankers hesitant to invest. However, many farm operators alleviated their capital requirements through government grants and subsidies. One profitable farm was funded by its parent company. A common trend is that acquiring funding with low or zero interest rates contributes heavily towards achieving profitability.

32% of VPF operators expressed that conducting research and development (R&D) takes substantial time and capital. Therefore, operators need to have a sufficient capital runway for commissioning the farm and creating standard operating procedures (SOPs) that they did not plan. In hindsight, many wished that they had raised more capital and communicated this to investors. Balancing R&D and commercial growing is discussed further in Section 4.4.3. If a business plans to operate a commercial farm, it may be worth outsourcing the building of the farm to an experienced developer to avoid costly efforts to integrate all the different technologies involved.

> *"I think the top reason why vertical farms crash and burn is they're undercapitalised. When you're building a farm, as you're operating it, you don't know how much capital you need."* – Robert Colangelo, CEO of Greensense Farms [73].

The capital market is highly stratified. Equity and private investments have funded many vertical farms whilst seeking high returns. However, vertical farms cannot achieve high returns until the cost of technology reduces, productivity improves, and farms can scale with the same fixed costs [75,82]. Problems finding the right capital source and misaligned investor expectations came up frequently as a common failure mode, as investors can push the wrong decisions. Farm operators require patient forms of capital that understand the long development cycle, similar to agricultural seed development and biotechnology. Careful planning, a good understanding of risk management, and effective communications with funding sources are mandatory and can help reduce this issue.

> *"He's out of patience on this, and he's all of a sudden frustrated that he's tied himself up into a capital-intensive business that grows $5 lettuces with $50,000 machines. He wants to see returns are in the order of 10 to 15 to 20 times what he's put in."* – CEO of a commercial vertical plant farm.

Cost components

The interviews discussed core cost components for CapEx and OpEx to identify considerations and typical values. These considerations have been collated and synthesised in Table 4.2.

Table 4.2. Cost component considerations

Type	Cost component	Consideration
CapEx	Rent	The cost of rent can be very high if placed in an urban context without any cost deduction resulting in an unviable business case. Profitable farms found that being placed on the outskirts of cities or in the countryside was economically preferable due to lower land costs. A long-term agreement should be sought to ensure security and avoid rent increases.
	Technology	High technology costs are a significant barrier for entrepreneurs, and they feel the costs do not justify purchasing unprofitable hardware. On the other hand, a higher CapEx can lower OpEx using the best available equipment. The cost of lighting was the highest technology cost and was reported to be a constraint for some farms scaling.
OpEx	Depreciation	Business plans often overlook depreciation. It is suggested to factor in at least a 30% CapEx refit after 10 years [297]. Depreciation typically accounts for 12% to 30% of OpEx [86,90,115]. Depreciation for a farm is reported by [115]: 15 years for the facility, 10 years for equipment, and 5 years for lighting.

	Electricity	Electricity accounts for 21% to 52.5% of OpEx [63,91]. The electrical efficiency of lighting plays a pivotal role in the profitability of a IVF. Methods to reduce energy costs by 20-30% and a theoretical 50-80% exist [115]. In addition, it is possible to negotiate rates from energy providers and utilise load shifting to optimise prices [303].
	Labour	Labour is likely to be the highest operational cost and is typically underestimated. Costs range from 26% to 56% of OpEx [62,86]. Labour costs can be reduced by 50% within several years of farm operation through semi-automation/full-automation, production processes, equipment layout and human resource development [63] which we explore further in Section 4.4.2.

4.4.2 Theme 2: Labour

> *"I assure you that you are underestimating labour, and it will be the biggest cost and the most likely failure of your farm."* – Matt Liotta, Founder of PodPonics [78].

Labour was the top reported problem for CEA growers in 2019 in a prominent industry survey [61] and is typically the highest operating cost [62,86,115]. These interviews revealed some of the challenges, tactics and considerations of vertical farms through the lens of labour. The ideas were disaggregated into two sub-themes: team and process flow (coding is illustrated in Figure 4.6 in proportion to occurrence within the dataset).

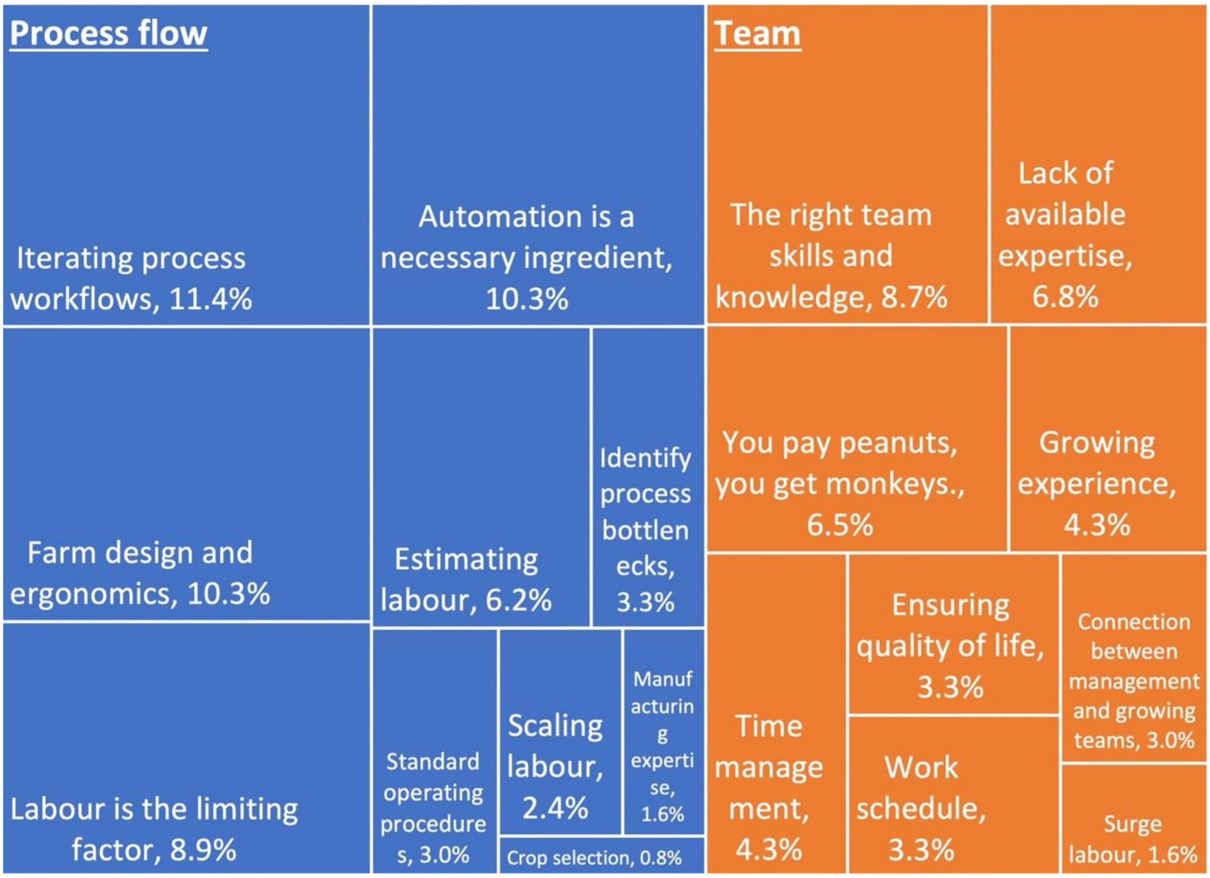

Figure 4.6. Labour sub-themes and codes.

Team

> *"With vertical farms, you are balancing horticulture, engineering, and economics. And it's like a three-legged stool; if one of those legs is weak, the whole thing goes down."* – Vertical farming and greenhouse consultant.

Vertical farms are operationally complex, requiring interdisciplinary expertise. Even with a viable business plan, a qualified and experienced team is needed in the skills illustrated in Figure 4.7. These skills can also be outsourced, but they must be considered. There are currently no standards and a lack of education in this new industry, making hiring and developing best management practices challenging for companies. Some operators report finding employees from similar industries (managers from mechanised food facilities, greenhouse growers and people, with cannabis farming experience). Smaller farms struggle with the broad skillset required due to increased labour costs.

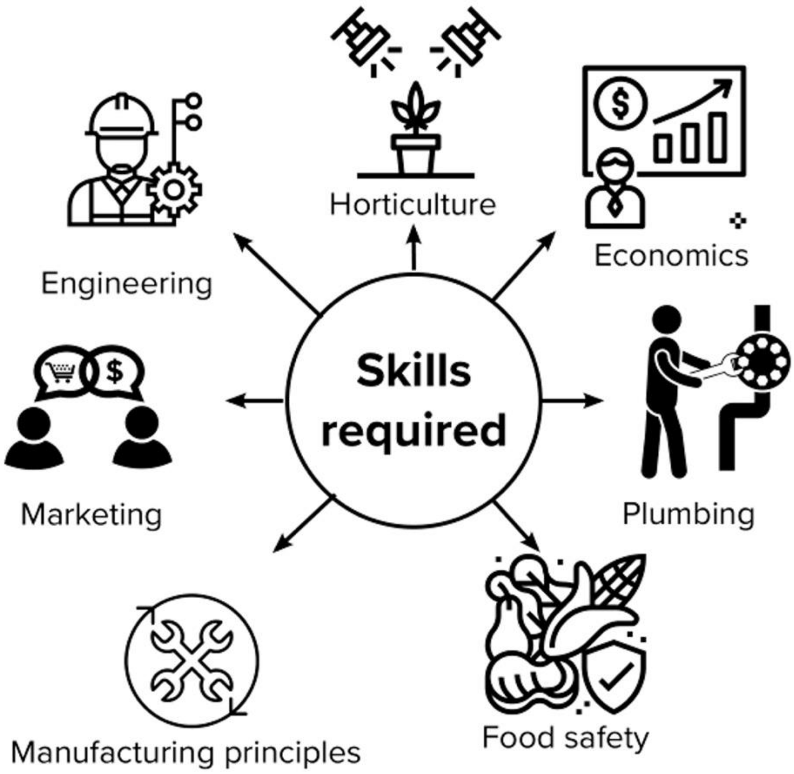

Figure 4.7. Skills required for a successful VPF operation.

For vertical farming to scale, there is a need for an educated workforce for senior positions. Quality farm labour requires farm education. Leveraging local universities or colleges to build training programmes is one successful approach that has been applied [78].

Maintaining a good connection between the managerial team and the growing team is imperative. Due to R&D, there can be a lot of uncertainty, and experienced leadership can help mitigate associated difficulties. One of the challenges across many farms was a disconnect between management and the shop-floor employees. This can result in low productivity, poor product quality and a lack of data collection. Developing SOPs was an integral way to reduce miscommunication. The goal is to design a farm that is not dependent on the competency, memorisation, or capability of any one individual. An example of good management was discussing with shop-floor employees how to remove their "pain points" and bottlenecks. They listen and act on their concerns whilst providing autonomy to apply their skills. Managers that did this reported higher than average labour satisfaction and engagement. All of the farms interviewed followed a weekly schedule for planning and delegating tasks.

An industry survey reports that 49% of CEA founders had no prior experience or knowledge in farming before starting their businesses [42]. Several of the farm operators in this study reported no experience either and struggled with learning the basics of growing. Growing experience significantly affected the consistency of product quality, yields, and waste rates.

> *"A key lesson that I learned early on is that you pay peanuts, and you get monkeys, right? If you pay a little bit more than minimum wage, you're retaining [your employees], cost of training will go down, your cost of recruiting will go down."* – CEO of a commercial vertical plant farm.

Vertical farms can provide manual work that is relatively simple that can be accomplished by elderly and disabled workers. Due to its repetitive nature, some farms decide to bring in volunteers, interns, or low-cost workers, which benefit the cost perspective of a VPF; however present challenges in terms of consistency, product quality and risks. Total costs may be higher from the cost of training and recruiting new employees frequently. Farm managers reported finding it challenging to correct nuanced mistakes (i.e. careless seeding) that volunteers made because they felt they were doing them a favour, resulting in crop loss. Low-paid staff may miss work more frequently due to sickness or court dates, take longer to execute tasks and potentially ruin crop cycles due to accidents (see Section 4.4.6). Providing financial incentives for farmhands to become team leaders improves performance.

Most vertical farms have a small core team working on a longer-term strategy, with a team of casual workers for farmhands. Operators used casual workers at a higher intensity during seeding, transplanting and harvesting, especially when they had to fulfil customer orders in the mornings. This can provide job opportunities for students, stay-at-home parents, or other demographics. Profitable and large-scale farm operators interviewed had highly competent and small management teams (having people with overlapping skills shown in Figure 4.7) supported by a large and unskilled part-time workforce.

Process Flow

Practitioners have labelled VPF as a combination of manufacturing processes and food production due to consistent control and production. Therefore, practitioners can treat VPF as a process suited to applying manufacturing principles [205]. The process flow is defined as sequential tasks that guide people to get work done. Its main objective is to streamline and standardise business processes.

A lens from which to view process flow is through accessibility, maintainability, and repairability. System designers and operators often neglect these aspects and end up with higher operating costs over the long term when equipment fails or parts are challenging to clean (explored in Section 4.4.4). Multi-layered systems with high grow beds that need to be accessed can become problematic as growers navigate the grow space. Operators who used equipment to access the high levels found that scissor lifts were cumbersome, expensive, dangerous and blocked access resulting in higher waiting times. Two profitable farms had two floors to access up to 12 layers of cultivation shelves and found this adequate.

From a farm layout perspective, operators should consider how people will move around the facility efficiently without collisions. There has to be sufficient space for operations and access between racks. It is recommended that 50% of floor space be allocated to the growing area whilst leaving the remaining area for operations, walkways, seedling production, processing, and equipment [115]. This may increase or decrease depending on certain factors (i.e. cold storage or mobile racking). As the facility scales, labour will scale differently from other factors. Two profitable PFAL operators explained that smaller growing rooms are better for labour productivity, minimise movement, and are easier to manage. These operators aimed to design their farms in line with their workers' potential to achieve a certain work speed per unit of crop (i.e. 60 seconds per lettuce head) [302]. Equation (4.1 shows how to calculate work speed. 500 m^2 partitioned cultivation rooms are reported to be a suitable size by operators however this requires further research. Kozai (2019) suggests guidelines on farm layout [113].

$$Work\ speed = No.of\ workers\ present \times \frac{Portal\ to\ portal\ hours}{No.of\ plants\ harvested} \tag{4.1}$$

Automation is not necessary for all vertical farms, according to Kozai (2018) [93], even though many operators thought it was. It can bring challenges such as high costs and highly-skilled workers to manage the technology, which is why it is important to assess cost-benefit before making decisions on whether to invest in automated technologies. For smaller farms, it is imperative to implement robust systems and processes that can reduce labour costs and not rely solely upon automation. All the profitable farm operators interviewed were only partially automated and relied upon manual labour for seeding and harvesting. The activities that should be automated according to the size of the facility are shown in Figure 4.8.

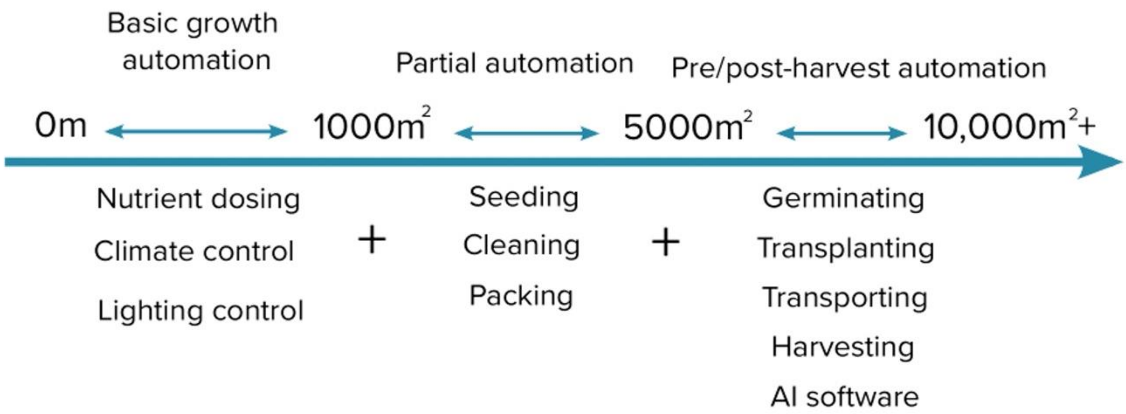

Figure 4.8. Automation types according to facility size (see [93,113])

In 38% of the data sources, practitioners described underestimating labour, and 53% discussed how labour was a limiting factor in their production. Labour was universally the highest cost across all the participants that reported their operational cost allocations. Addressing bottlenecks on a farm can improve efficiency and production output. For example, one farm operator recounted overcoming process bottlenecks by switching from growing in pots to trays, cutting with hedge trimmers instead of scissors, and cumulatively shifting their gross margins from –30% to +30% (see Figure 4.9 a). Introducing machinery for cleaning, packaging, or seeding can yield similar step changes that improve productivity and labour satisfaction. We asked interviewees to draw their perspectives on the change of performance in their farm since becoming operational to understand the learning curve and the impacts of bottlenecks. Figure 4.9 shows two farms with bottlenecks in their production.

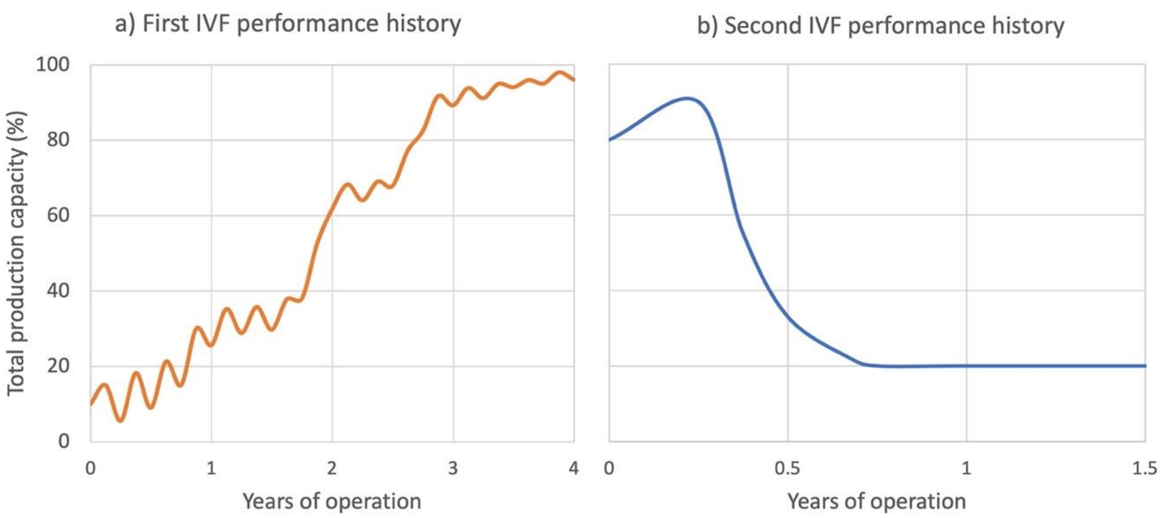

Figure 4.9. The production performance of two indoor vertical farms a) a multi-container facility 1000 m^2 that overcame three bottlenecks in production and b) a 450 m^2 basement facility that had a process bottleneck with the packaging machine that inhibited production.

Operators found it helpful to set a target time per crop (for example, 60 seconds of work per head of lettuce). Additionally, using surveillance cameras can help managers to understand where mistakes are being made to adapt SOPs and improve the flow of operations. Successful farms implemented visual signals and management alongside environment 'nudging' to create or sustain desired employee behaviour.

4.4.3 Theme 3: Growing

The interviews revealed considerations for achieving the best possible product quality whilst ensuring food safety and balancing R&D. The codes were grouped into three sub-themes: growing factors, food safety, and effort dedicated to R&D (illustrated in Figure 4.10 with coding represented in proportion to occurrence within the dataset).

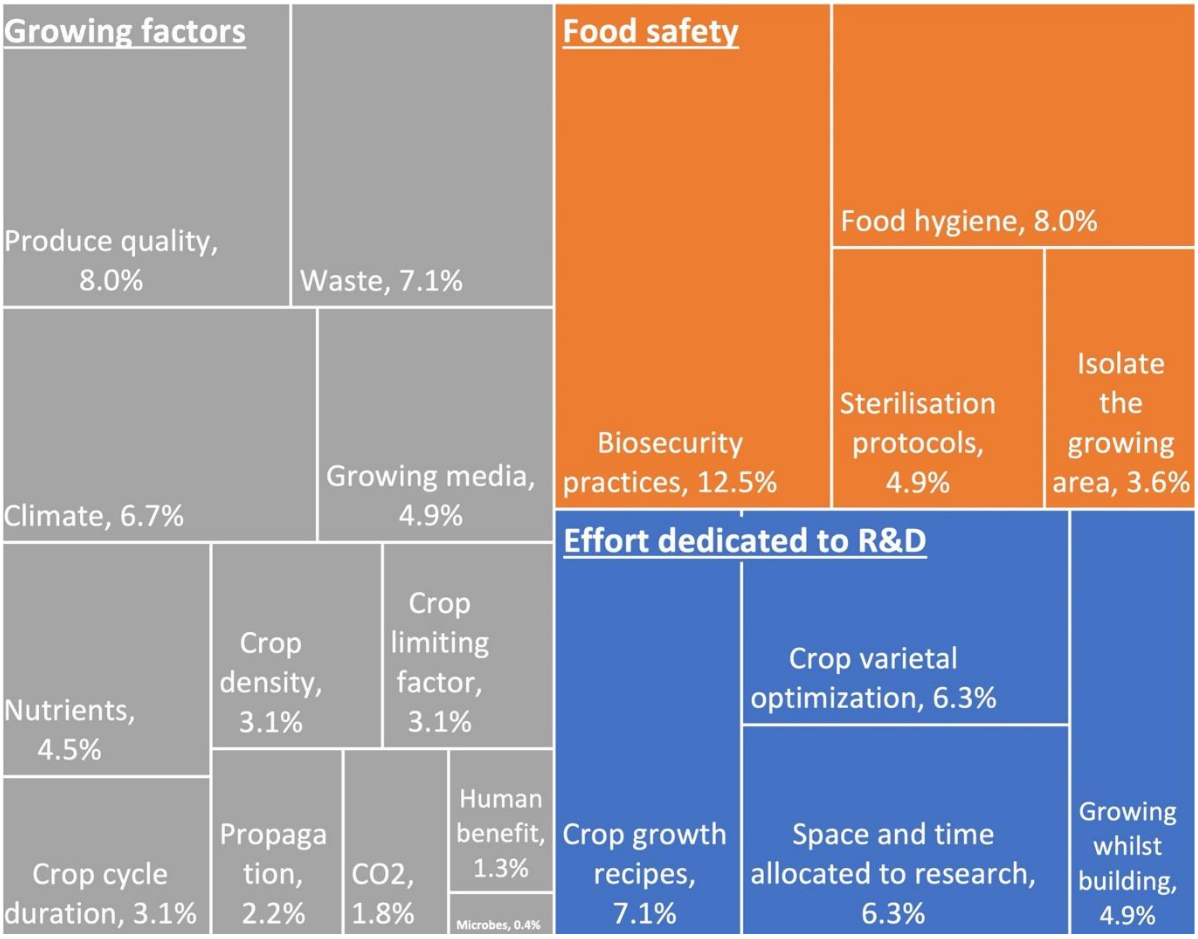

Figure 4.10. Growing sub-themes and codes.

Growing factors

The interconnected factors that contribute towards growing produce were explored and are visualised in Figure 4.11. The growing factors influence biomass yield, produce quality, crop cycle duration, waste rates and the crop limiting factor. Table 4.3 links the growing factors to relevant literature that can aid growers to implement practical changes. The anecdotal reports from interviews are discussed to glean any insights and expose voids in the literature.

Figure 4.11. Growing factors are shown as outputs (orange) and inputs (yellow).

Table 4.3. Growing factors

Growing factor	**Relevant literature**
Nutrient solution pH	[304–306]
Air temperature	[307–309]
Water temperature	[310–312]
Vapour pressure deficit (humidity)	[313–317]
Carbon dioxide	[318–320]
Airflow	[321–323]
Light spectra	[324–326]
Daily light integral	[319,327,328]
Light uniformity	[329–331]

Microbial communities	[332,333]
Nutrient intensity and flow	[334,335]
Nutrient composition	[336,337]
Water oxygenation	[338,339]
Propagation	[302,340]
Growing media	[341,342]
Growing density	[343–345]
Micro-climates	[317,346]
Growing experience	[75,201]
Pests	[347]

Crop limiting factor

Understanding crop requirements to identify and improve the limiting factor is key to successful VPF system design. Operators can focus on low-hanging fruit by handling the macro-requirements of crops such as temperature, vapour pressure deficit, CO_2 enrichment, and integrated photosynthetic photon flux density before finetuning micro-elements like light spectra, nutrient composition, microbial communities and oxygenating water. For example, several operators reported that they did not see noticeable improvements from a change in light spectra because their climate control was not optimised. A challenge for VPF is understanding Liebig's Law of the Minimum, which states that growth is dictated not by the total resources available but by the scarcest resource (the limiting factor) [348]. Strategies to identify the scarcest resource are needed. For profitable farms, they stated that the limiting factor in their production was presented as tip burn in leafy green production.

Crop density, climate control and pests.

> *"All the heat, humidity, and pests that result from these processes are amplified in a denser growing environment. Vertical farming is not about how much production you can possibly cram into a space. It's about growing better food closer to market and maximising your production as a function of the resources you invest, such as capital, light, water, energy, and labour."* – Chris Michael, co-founder of Bright Agrotech [200].

There was a contrast among some farm owners' thoughts around crop density. Some interviewees thought that the highest crop density possible was desirable, whilst others recognised the risk posed by increasing density to adequately control micro-climates to the detriment of plant quality. Heat and humidity easily increase with higher densities, increasing the risk of pests and reducing yields and quality. Managing the growing environment becomes increasingly complex, with higher crop densities resulting in physiological disorders.

An air temperature between 18 and 25°C is suitable for most crops in indoor vertical farms [127]. The vapour pressure deficit should be set between 0.8 and 0.95 kPa, and optimally 0.85 kPa [349]. Air current speed should be set between 0.5 to 1.0 ms^{-1} to disrupt the boundary layer flow in the plant canopy and promote gas exchange [127].

CO_2 enrichment

Many smaller operators rely on atmospheric CO_2 (400-420ppm) because they compared their operation to open-field farming which does not require CO_2 injection. However, for airtight facilities with higher crop densities, adding CO_2 will benefit production substantially [115]. In Japan, most operations use CO_2 enrichment as they realise this is critical for profitability. For lettuce, 1200ppm achieves the maximum net photosynthetic rate [319], however, this can be limited due to standards of ventilation requirements [320]. Japanese standards which are based on body odour perception are counter-productive to PFAL operation, as there is no evidence suggesting CO_2 at such concentrations is detrimental to comfort or health [320]. Therefore, there are opportunities by adapting such standards to improve the productivity of an IVF.

Crop cycle duration

> *"Most of these [vertical farming] operations produce baby leaf [salads]; they produce very small plants at a very high density, that are cut and removed at a very young stage. That's why most of these companies are not producing full-sized plants, because managing the environment is difficult, and they start to have nutritional and physiological disorders."* – Vertical farming and greenhouse consultant.

Farm managers noted that a short crop cycle duration benefited production. Smaller crops (like baby leaf salads or microgreens) were quicker to produce, preferred by the consumer, and less prone to physiological disorders and diseases. This was counter-intuitive to some growers who initially assumed bigger crops would be better. Larger crops would require more labour and present challenges with managing microclimates. Microgreen farmers felt that their cultivation was more manageable and perhaps a suitable starting point to understand the basics of VPF and hydroponic cultivation.

Nutrient solution, sterilisation, and microbe management

Many practitioners used a general nutrient solution for their crops. Lu and Shimamura (2018) provide guidelines on proven nutrient solution formulae for leafy vegetables [127]. Finetuning composition to match absorption characteristics of the crops can yield improvements in quality. In the future, the concentration of individual ions should be measured and managed separately, and [350] provides guidelines to achieve this. Maintaining a pH value of 5.0 to 7.0 and a root zone temperature of 18 to 22°C is suitable for most crops in IVF [127].

When asked about sterilisation procedures, most farms used ultraviolet light filters, Ozone or hydrogen peroxide to reduce contamination risk within the growing system. However, sterilisation can also kill beneficial microbes, reducing the overall quality of the produce. Some operators also report unexplained imbalances in the nutrient solution that affected plant growth, which they suspected was from not deep cleaning the systems often enough. They explained that this has received little attention in the academic literature which could be fertile territory for more research.

Germination and propagation

VPF operators reported that seeding and propagation were the most critical steps in the growing cycle to achieve the best possible harvest. However, several farms found that propagation was their limiting factor. For example, large yield fluctuations depended on who was seeding the trays/pots at a given time. Standardised propagation or automated seeding resulted in more consistent and better yields. Guidelines on propagation management have been taught as part of a training course [302].

Waste

Waste, defined as shrinkage, unsalable produce, unsold produce and inedible biomass, varied considerably depending on the business, crop selection and growing experience. Waste and shrinkage can minimise profitability for a farm and occur at any point in the growing chain. Growers reported waste rates ranging from 2% to 22% in the growing process. Two profitable farms reported 10% to 15% wastage rates depending on cultivars and quality standards.

Food safety

Food safety is an essential part of any agricultural operation. However, there was much ambiguity about best practices for VPF. There were two camps of interviewees. On one side, there is the cautious approach with almost sterile environments with employees wearing protective clothing. These farms have robust sterilisation protocols and follow strict compliance schemes.

On the other hand, some operations treat their IVF less seriously, viewing an indoor farm as a traditional farm that does not need to be sterile and clean but maintains light food hygiene standards. Figure 4.12 shows the reported practices. This section breaks down views on sterilisation protocols and food hygiene.

Figure 4.12. Reported food safety practices

Most farms visited and interviewed mainly used diluted hydrogen peroxide for sterilisation protocols for cleaning equipment, disinfecting seeds and recirculating the growing system. As the hydrogen peroxide breaks down into the water quickly, this renders the chemical harmless and compatible with organic production—this chemical reduces the risk of fungal outbreaks. The application of hydrogen peroxide in hydroponics is relatively unstudied. However, one recent study found that dosing is necessary for crop quality and can potentially improve the viability of organic hydroponic fertilisers [351]. Other sterilisation methods include ultraviolet lamps, Ozone, heat sterilisation, silver/titanium oxide utilisation, sand filtration and oxygen bubbling [352]. There is no ideal solution, and each method has its pros and cons [127,353]. One consultant emphasised that sterilisation kills beneficial microbes and harmful microbes, hindering crop quality. This requires further investigation.

Hygiene education should be given to operators to inform practices that mitigate contamination risk. There are no standards for VPF. However, the practices in Figure 4.12 help prevent the worst-case scenario of any pathogen or pest outbreaks. Many farms did not use any pesticides at all in their production. Additionally, one of the value propositions of VPF produce is cleanliness which does not require washing and has a longer shelf-life. Strict hygiene practices achieve these benefits. The highest contamination risk comes from the nutrient solution and water; therefore, it is best to avoid direct contact between the water and the crop leaves. Kubota (2019) gives examples of conducting microbiological testing for water quality and crop leaves [353].

Hiring a food safety consultant before designing a facility is advised to meet compliance demands by wholesalers and mitigate any contamination risk or potential liability issues. However, each farm had its own practices because there is a lack of literature in this area.

The effort dedicated to research and development

> *"One of the biggest challenges was really that while we were producing and scaling, we had to conduct R&D. Not only did we have to have time for R&D, but also money and space. So I think it was a killer of a formula." – Pawel Hardej, CTO of FarmedHere.*

Unanimously, farms developed technology (software and hardware) whilst trialling crop cultivars. Consequently, farms are raising capital, hiring skilled employees, identifying customers, selecting crops, packaging, finetuning processes and getting the product to their customers at a high level of quality. Juggling all these tasks burns cash faster, as farms require space, effort, and time dedicated to research and development to improve all these aspects. In some cases, operators allocated 50% of farm space to R&D. This presents disorganisation, as operators dilute their focus to build and operate their farms simultaneously. Eventually, some begin to shift their business focus towards technology development as the technology is "evolving too quickly to jump in as an operator". Profitable PFAL operators interviewed focused more on well-researched crops and less on experimentation, dedicating only 5% of their facilities and efforts to R&D and new crop types.

Discovering and selecting the appropriate crop cultivars is part of VPF R&D. Crops with low labour demands or that are easily automatable present better unit economics. Moreover, crop breeding is presenting cultivars suitable for VPF production. Profitable farms were working with seed companies to develop new cultivars. New lettuce varieties are currently being scaled which are capable of larger harvest weights with tip-burn resistance and therefore reduced labour requirements [64]. Before designing their facility, many farms were unsure what they wanted to grow, experimenting with a large diversity of crops and then whittling down to the most profitable crop varietals that best meet the local market conditions.

4.4.4 Theme 4: Technology

Technology selection involves many costly decisions that determine the economics and scalability of the operation. This section examines the sub-themes generated from the interviews: pushing a square peg into a round hole, being intentional with data, and system considerations (coding is illustrated in Figure 4.13 in proportion to occurrence within the dataset).

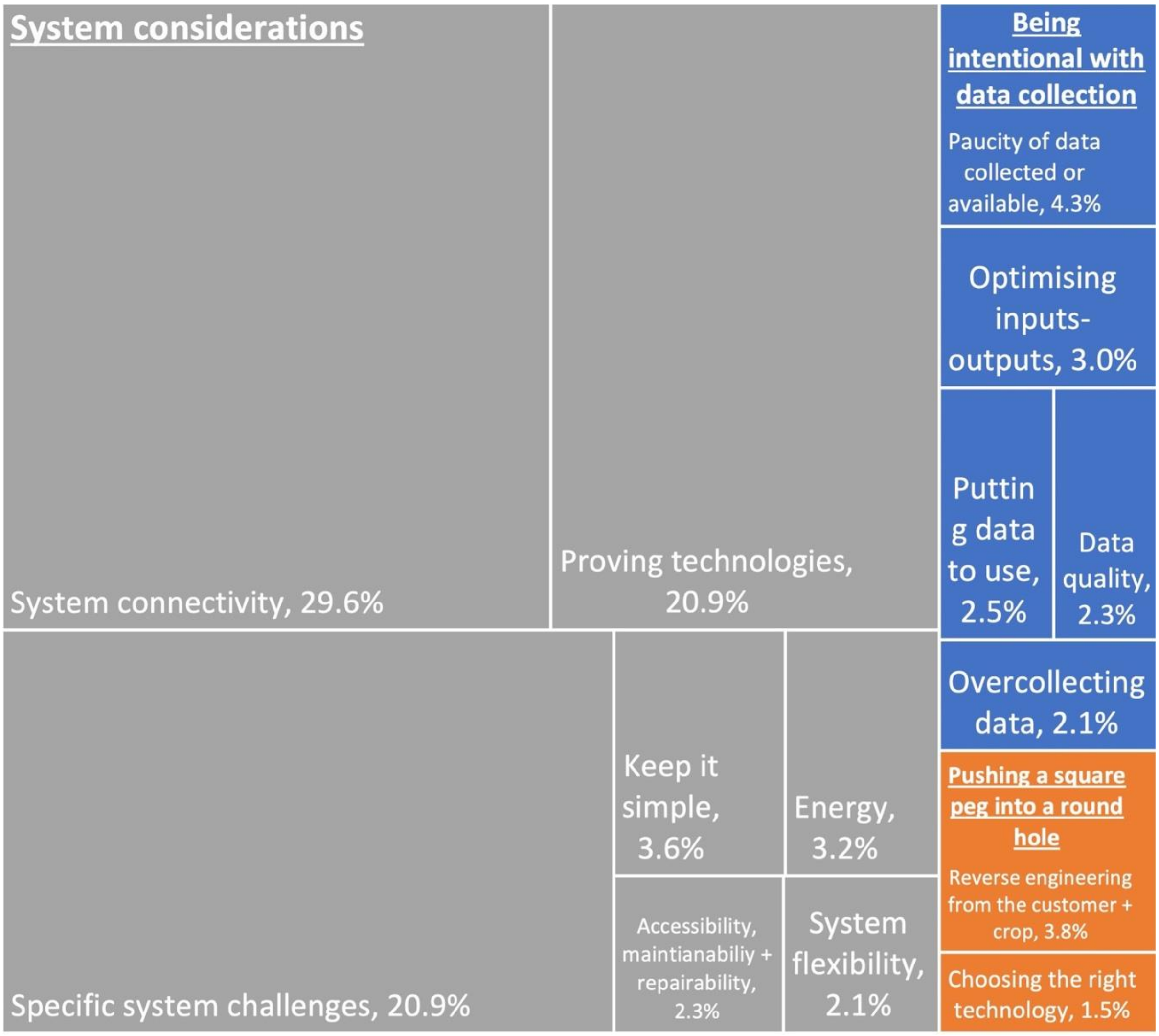

Figure 4.13. Technology sub-themes and codes.

Pushing a square peg into a round hole

A typically reported mistake is purchasing technology before identifying the problem that the farm hopes to solve. A market analysis should determine what crops to grow that may be challenging to grow traditionally and are subject to risks in the distribution process, system, or time (temperature, seasonality). The product can then be defined alongside a target customer and price point. Then farmers can reverse-engineer the most appropriate technology and farm design to achieve competitive unit economics and product quality for their customers. The appropriate solution may not be a vertical farm but, in fact, a standard greenhouse or hoop house. Selecting the most appropriate technology is essential.

Data

> *"When I looked at vertical farming, there is just very little data out there that's published and reliable."* – Robert Colangelo, CEO of Greensense Farms [73].

An IVF's outputs can be highly precise due to controlled and measured inputs and environmental control. Crop growth and phenotyping can be optimised with millions of parameter combinations. Data can augment production, improve farm yields, and reduce labour time through better decision-making when applied appropriately. However, some farms try to collect everything possible without a coherent data strategy, spending capital and effort without leveraging the data. Converting data into meaningful and actionable insight is paramount. Optimising the production as a function of the resources invested is where VPF has the potential to excel due to the unprecedented feedback loops (seed to harvest) achievable within a year. These feedback loops make artificial intelligence (AI) compelling for IVFs, and almost all interviewees wanted to incorporate AI, but the costs were prohibitive.

> *"It's very important to build up the foundation for use of machine learning [AI], because, at some point, you understand that you cannot calculate it yourself anymore."* – Manager of a commercial vertical plant farm.

Many farm operators interviewed did not keep track of standard metrics because they were overwhelmed with operations and delivering sales. Lack of standardisation and available data present significant obstacles to comparing and establishing a performance baseline. Many participants had to build their proprietary software platform to store and manage data to iterate crop growth recipes and link harvests to sales. They noted an absence of available data, finding data from the literature as indicative.

At a minimum, farms should measure the metrics in Figure 4.14 for each crop type. This will allow them to build an operational history. In addition, by measuring these metrics, farms will be more likely to manage these variables and show investors their performance history if seeking funding.

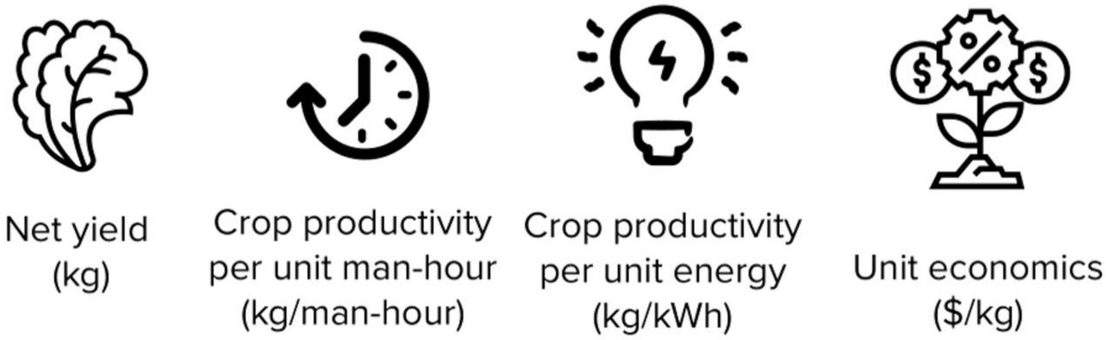

Figure 4.14. Suggested key performance metrics.

System considerations

Several farm operators felt the category was still immature and that many technologies were unproven. As a result, farm operators shifted systems repeatedly, trialling different growing systems or lights. Lighting is a prohibitive cost for many, and some farms found through trials that when comparing cheaper lighting solutions to reputable brands, their yield and quality were the same with a higher ROI (see crop limiting factor in Section 4.4.3).

> *"The incentive for the technology vendors to appear more efficient and productive than their competitors fosters a culture of greed and dishonesty."* – Vertical farming and greenhouse consultant.

Unanimously, all the interviewees asked about yield estimations, and productivity claims found them to be overestimated and inaccurate. With so many interconnected factors at play, this is not surprising. In some cases, operators reported achieving only 10-50% yields stated by their system vendor because of labour workflow and environmental control challenges. Therefore, it is worth adding a contingency margin to projections given by vendors.

> *"Don't buy it if you can't clean it."* – Matt Liotta, Founder of Podponics [78]

For container farms, operators reported an antagonistic relationship between light, layout, heat and workflow issues and that HVAC was the limiting factor in production. For vertical towers, five operators were either using or had tried vertical tower systems and experienced leaks, dripping of nutrient solution onto lower plants (a health risk in Section 4.4.6), physiological plant disorders (plant orientations effect on plant quality is unknown in the literature) and ergonomics issues (neck and back pains). These are some examples of how system performance is exaggerated.

> *"LED lights are going to fizzle out, mechanical systems are going to fail, and pumps will need to be rebuilt. It would not be crazy to suggest that up to 70% of a vertical farm system will undergo some level of replacement or repair within a 10-year window.* – Chad Sykes, Founder of Indoor Harvest [297]

Many interviewees expressed the need to keep technology simple and avoid reinventing the wheel. Overengineered systems can have many failure points, resulting in high repair costs. High humidity can cause mechanical system failures due to rust. Ease of access, maintenance, and repair, are fundamental aspects of viable VPF technologies. Many farm owners found that their systems were more problematic to upkeep than anticipated and most challenges began to arise after several years of operation. A preventative maintenance plan can mitigate the risk of equipment failure and its impact on finance or production. Profitable farm operators that were interviewed planned for this in advance, and used simple yet proven technologies whilst introducing automation only when they were able to pay back the costs through labour reduction savings.

Smaller farm operators reported that system flexibility was an important factor in decision-making for technology. Agility can be significant for smaller farms that target a retail market. Specifically, mobile racking systems allow for higher space utilisation, and DFT systems can allow multiple crop types.

When asked about the most challenging aspect of developing a farm, system integration (synchronising systems to interact and adapt to data and track compliance) was at the top for most interviewees. Additionally, many VPF operators overlooked HVAC, with engineering companies using inappropriate assumptions from other industries to size the requirements [293]. An adequately engineered HVAC system can remove humidity and heat whilst enabling airflow management across the plant canopy and becomes increasingly important as crop density increases. When profitable farm operators were asked what they would do differently for their next farm, efficient and agricultural-grade building materials were emphasised as an opportunity to reduce building costs by 60%. This could encourage further custom-built PFALs as opposed to using old structures that usually come with complex challenges such as accessibility and food safety.

4.4.5 Theme 5: Strategy

Strategic decisions around location, market and business goals influence the success of a VPF project. In this section, we examine the sub-themes generated from the interviews: market, location, focus business goals, build collaboration, create a backup plan and start with a pilot (coding is illustrated in Figure 4.15 in proportion to occurrence within the dataset).

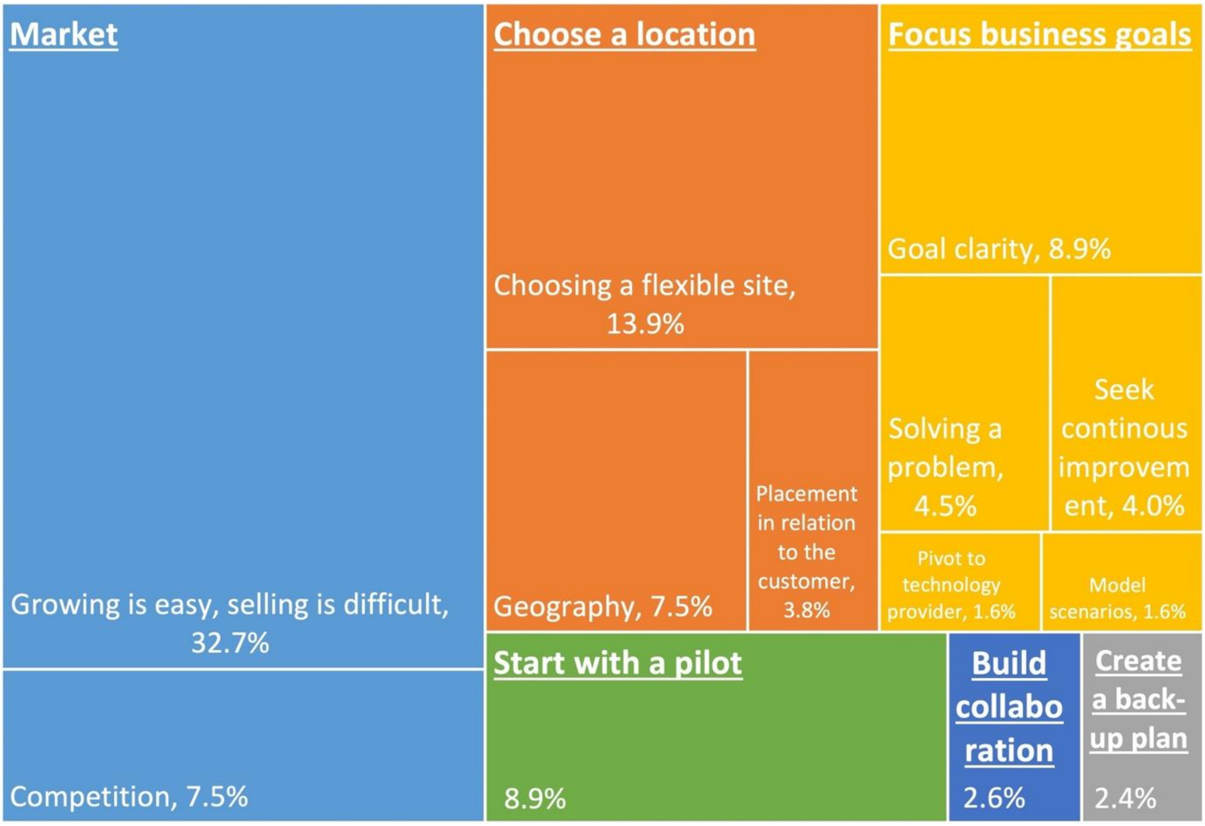

Figure 4.15. Strategy sub-themes and codes.

Market

The target market and local context are pivotal in a viable strategy. VPF differentiates itself due to benefits discussed elsewhere in this book, and operators reported that customers were most interested in the pesticide-free quality and are increasingly willing to pay a premium for local produce [202,203].

Participants found that the most challenging part of the production was not growing but selling produce and getting it to the customer. The industry is segmented between large-scale vertical farms producing large quantities of leafy greens for wholesale markets, medium-scale farms focusing on herbs and niches (like edible flowers, microgreens, and animal fodder) and many small farms serving retail markets a range of crops. Each customer type had its respective trade-offs. Operators said that although retail customers paid more, they had comparable work requirements and costs as wholesale customers to sell dramatically less produce. A more sophisticated and large farm is needed for wholesale customers, but distributors can take a high percentage of sales (scale and customer acquisition save costs). Profitable farms stated that access to a big market was a key factor in their success, and this is likely why Japan has some of the most successful indoor vertical farms. Japan has a health and hygiene-conscious population that is used to paying a premium for high-quality fruit and vegetables (up to 320% price increase for PFAL lettuce compared to conventional). Some farms are distributed in their customers' locations where crops are transplanted from a warehouse, achieving the benefits of wholesale production with the power of retail sales with lower distribution costs—Section 4.4.5 details suitable locations for these customer models.

Forming a pricing strategy based on the unique value of VPF is crucial to ensuring sustainable unit economics. Food produced indoors has fewer unknown variables, unlike the outdoors, and therefore the price should reflect the added security. In several cases, where vertical farms found product-market fit in their local context, their sales outgrew their production. Even when charging a 20% premium over organic produce, their produce sold out in supermarkets. Learning that organic farming uses pesticides helped drive customer sales. Most farms noted that a growing contract was the best way to mitigate marketing risks but that they were hard to negotiate as most customers were reluctant. They also enabled operators to insure their crops, reduce their risk profile and reduce waste.

IVFs can produce unique combinations of crops with synchronised harvest times. One operator claims that the only way to compete is by offering customers a product they cannot find elsewhere. To achieve this, it is necessary to integrate continuous feedback from the target market, marketing team and the growing team. In a couple of cases, competitor traditional and vertical farms would engage in predatory pricing strategies (undercutting their product at loss-making levels). Market dynamics were highly correlated to the seasonality of conventional produce.

Build collaborations

Farms are increasingly finding that collaboration amongst technology providers, farms, landlords, academics, energy providers, and governments will be essential to advance the sector. This is echoed in the literature [30,76,77,79,80,82] and is also becoming apparent through an increase in the membership of vertical farming industry groups such as FarmTech Society [354] or Japan Plant Factory Association [355]. Additionally, vertical farms can reduce their risk profile by drawing from expertise without the associated human resource costs by building business collaborations. For example, farms can work with lighting providers and system providers to trial new systems. They can synergise with their location to provide ecosystem services for their landlord in exchange for subsidised rent. Working with educational institutions can access university researchers to conduct R&D.

Choosing the right location

Site selection is key to the philosophy behind VPF, especially in urban environments and is one of the most important decisions that will determine the success of a project. Fundamentally, the goal of VPF is to disrupt an agricultural system more efficiently and sustainably. Three core factors determine whether a location is suitable for a vertical farm: i) placement in relation to the customers, ii) the building and its characteristics, and iii) the geography and environmental conditions.

Each farm is wholly unique, and there is no one-size-fits-all approach. However, based on the learnings reported, some common trends amongst desirable sites are represented in Figure 4.16.

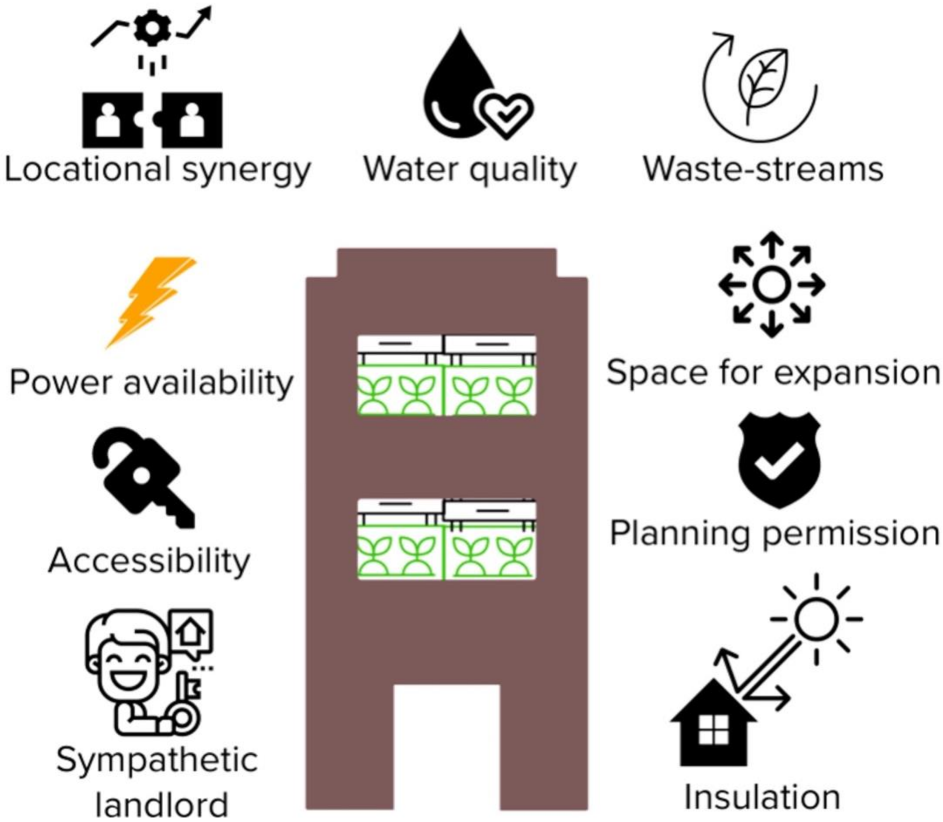

Figure 4.16. Building considerations.

Planning permission can be challenging due to a lack of zoning codes. Potential operators should be careful to identify power availability prior to construction. Accessibility will reduce logistical difficulties and improve labour efficiency. Looking for synergy with the building and other businesses is a way to build collaboration, improve resilience and reduce overheads. VPF should synergise with the building location as much as possible, taking advantage of opportunities to recycle heat waste, CO_2, or waste. Other opportunities include: providing education to local schools or universities, being placed near power plants to utilise electricity during off-peak hours, sub-letting expansion space to other companies and being next to a clean water supply. Companies that place their farms in locations with strategic alignment with government initiatives (near a new power plant facility or with sustainability priorities) will also improve their likelihood of receiving financial support.

Participants expressed that not every region is suitable for a vertical farm, whether indoors or using natural lighting. Successful farms pick a location where operators can solve a problem for their local market. For a vertical farm that does not have proper climate control or is exposed to natural light in a greenhouse set-up, it is essential to check environmental numbers with geographers regarding temperature and daily light integral. Lastly, developers that would like to incorporate renewable energy should consider the regional prospects. One farm reported that they could recapture 86% of their energy through waste heat and convert this to geothermal power. Other farms reported capturing solar energy to power their entire farm. Renewable energy-powered farms are becoming increasingly important to address the environmental impact of artificial lighting which is discussed further in [356].

VPF can vertically integrate the supply chain and take over distribution responsibilities; however, this complicates logistics for a farm. Therefore, some operators choose to outsource distribution. There are three distribution trends amongst vertical farms illustrated in Figure 4.17.

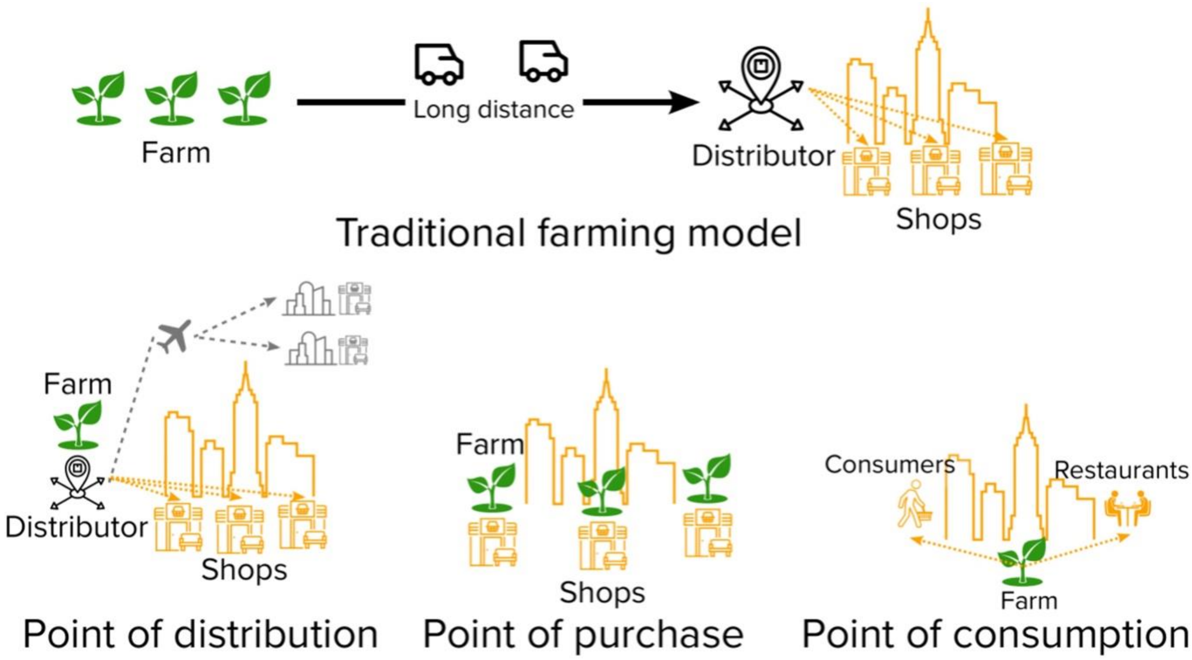

Figure 4.17. Vertical farming distribution models.

Placing a farm at the point of consumption is suitable for small farms targeting retail customers that benefit from a partnership with their landlord or co-sharing a space to reduce the high cost of the rent. VPF can also be co-located with traditional farms and provide fodder for livestock. Placing a farm at the distribution point, typically in a peri-urban environment, is suitable for larger farms that target wholesale markets. Placing a farm at the point of purchase eliminates distribution costs and middle management, improving unit economics.

Focused business goals

VPF is an exciting endeavour with opportunities to tackle many issues, but practitioners must ground their vision in reality and pick a problem they want to solve. According to several farm owners, those that try to grow food and develop technology simultaneously struggle to do well and eventually have to pick one [78]. VPF companies should know what their goal is and apply the 80/20 rule to identify the company's best assets and create maximum value. Farms should choose their priorities amongst the following values: aesthetic, social, education, health, economic, environment, research, and technology development.

On the other hand, only a few farms focused solely on growing. Some claimed they would fail if they had focused entirely on growing, most likely because they were small vertical farms that did not benefit from economies of scale. Smaller farms likely require alternative revenue streams to compensate, as described in Section 4.4.1. Therefore, it is advisable to model and test different business models and growing scenarios to compare the most appropriate strategy.

Start with a pilot

A pilot farm is a small-scale version of a planned facility enabling teams to apply their knowledge, make small mistakes, and find a product-market fit. A pilot reduces financial risk by keeping a project low-cost and validating the business plan. It also allows operators to select specific crops and test the appropriate system whilst gaining customer feedback without investing large sums of capital. The goal is to highlight any problems in system operation, plant growth and marketing.

4.4.6 Theme 6: Risks

VPF is a financially high-risk endeavour with a high chance of failure due to vast uncertainty regarding labour, growth, and economics. Despite this, there is little understanding of the risks associated with vertical farming specifically and what causes them to close down. IVF protects agriculture from outdoor risks that are typically hard to control. For example, a greenhouse is subject to weather and climate risks and a traditional farm is even more so. IVFs have managed to de-risk many of these factors from agriculture. However, it has traded these for new risks that have yet to be fully understood. We asked participants about the challenges and risks they faced when operating their farm. If the farm had closed down, the objective was to explore the root cause. The theme is split into a risk taxonomy and a discussion of the failure modes.

Risk taxonomy

From all the data items, reported risks were categorised into financial (Table 4.4), environmental (Table 4.5), production (Table 4.6), labour (Table 4.7), technological (Table 4.8), political (Table 4.9) and market risks (Table 4.10). A risk taxonomy can enable management teams to control risks more efficiently, plan risk-reduction actions, and avoid knee-jerk reactions. However, this risk taxonomy is exploratory and does not categorise risks in terms of likelihood or impact. Each farm considered was a unique case, and they did not have robust risk reporting protocols to provide detailed information. Moreover, as a young industry there will likely be risks that operators have not experienced yet. The 'percentage of farms' is relative to the sample size that reported the risk. If the percentage is 0%, that indicates the risk is known, but no farm operator within the sample had encountered it.

Financial risks

Table 4.4. Financial risks descriptions

Type	Source of risk	Description	% of farms
Internal	Debt risk	Unable to repay loans resulting in penalty fees and interest.	3.4
	Misalignment of investor's expectations	Investor's expectations do not align with the goals of the business resulting in diluted strategic focus.	19.6
External	Funding risk	Unsuccessful in acquiring funding and inability to sustain capital runway potentially resulting in bankruptcy.	16.8
	Electricity price	Increased energy costs resulting in lower profit margins.	6.7
	Rent price	Increased rent costs resulting in lower profit margins.	3.4
	Liquidity risk	Difficulty in converting assets into cash.	0
	Nutrient price	Increased consumable costs resulting in lower profit margins.	6.7

Environmental risks

Table 4.5. Environmental risk descriptions

Type	Source of risk	Description	% of farms
Internal	Daily light integral	Insufficient light intensity and duration to support the crop type grown	3.4
	Temperature fluctuations	The farm is susceptible to heat waves or freezing temperatures from inadequate climate control.	13.3
	Airflow/humidity	Temperature hot spots and lack of sufficient airflow and humidity control prohibit uniform plant quality.	3.4
	Organic acids	Plant hormones affecting crop quality and growth requiring frequent disposal of nutrient solution.	0
	Irrigation risk	Problems with irrigation systems providing water and nutrients to plants (clogged pipes or filters).	33.6
	Fire	A fire may result from a faulty electrical hook-up, a lighting malfunction, or other reasons.	0
External	Pandemic/Epidemic	The effects of a pandemic could require higher food hygiene practices, farm closure due to employee sickness, and loss of customers.	13.1
	Earthquake	An earthquake which could cause structural damage, electrical problems or cracked pipes.	6.7
	Flooding	Flooding of the facility or area externally resulting in a lack of workforce or reduced productivity.	27.1
	Typhoon	Typhoon in the region affecting electricity availability, building or workforce.	0

Production risks

Table 4.6. Production risk descriptions

Type	Source of risk	Description	% of farms
Internal	Contamination	Improper cleaning protocols or human contact can result in unwanted bacteria, fungi or pests.	13.3
	Process bottleneck	Manual work or limited machinery capacity may result in scaling back production capacity of farm.	6.6
	Shrink or waste	Waste from mishandling, improper storage, or delays in the	10.3

		supply chain can result in reduced yield and sales.	
	Plant diseases	Plant diseases could result in crop failure, reduced yield and reduced sales.	16.8
	Human pathogen	Adverse health impacts on customers that could cause serious liability consequences.	0
	Pest outbreak	Pests may infest the facility resulting in crop failure, reduced yield and a deep clean of equipment.	23.3
	Physiological disorders	Combination of growing factors may result in defects such as tip burn, necrosis, chlorosis, and shortened stem rotting. This results in reduced product quality and sales.	30.0
	Flooding	A leaking system may be a hazard to employees and reduced productivity.	27.1
	Crop uniformity	The crops produced are not consistent due to challenges with airflow, temperature, lighting, nutrients, etc.	6.6
External	Electrical outages	Light, irrigation, climate control, and automated systems are dependent on power availability. May result in crop loss.	6.6
	Delivery issue	Product is damaged in transit (shrinkage, left at room temperature or damage) or distribution is delayed.	3.4

Labour risks

Table 4.7. Labour risk descriptions

Type	Source of risk	Description	% of farms
Internal	Allergic reactions	Reactions due to crops, insects or chemicals could cause severe and dangerous reactions in some people.	6.6
	Chemical exposure	Exposure to Ozone, hydrogen peroxide or other chemicals that could harm employees.	3.4
	Human error	Improper seeding, overdosing nutrients or pH, careless harvesting, etc. could impact crop quality and yield.	53.3
	Staffing shortage	Reduced productivity and capacity to meet customer orders.	13.1
	Industrial accident	An injury when operating machinery or a collision of objects.	6.6
	Overexertion and repetitive strain	Manual work leading to employee injury that can result in the loss of employees and a liability issue.	6.6
	Slips, trips and falls	Falling over can harm to employees and pose a liability issue.	6.6
	Loss of expertise	Loss of a skilled employee, such as the head grower, could impact production and expected improvements.	0
	Lack of management qualities	Management may not be sufficiently experienced. Lack of connection between management and growing team can also result in reduced productivity.	0
External	Shortage of skilled workers	Not enough skilled workers in the local area to work on the farm for specific roles.	13.1

Technology risks

Table 4.8. Technology risk descriptions

Type	Source of risk	Description	% of farms
Internal	Overengineering	Using technology that is above the required specification or adds unnecessary complexity.	6.6
	Equipment failure	Problems with HVAC, lighting, refrigeration, growing systems, automation or software issues.	33.6
External	Technological advancements	Advancements lead to obsolete technology which is no longer competitive	6.6
	Lack of continuity from supplier or vendor	Initial provider is not available for guidance or part replacement causing challenges for maintenance and troubleshooting.	6.6
	False information provided by supplier/vendors	Reduction in production capacity and increase in labour costs compared to estimates.	13.1

Political risks

Table 4.9. Political risk descriptions

Type	Source of risk	Description	% of farms
Internal	Internal company disagreement	Lack of strategic alignment leading to loss of employees, productivity or product quality.	6.6
	Landlord dispute	Change in terms of agreement leading to the requirement to relocate.	10.3
External	Governmental policy	Change of policy could benefit or hurt production.	3.4
	Government ban	Government bans a crop type due to a food safety scare.	3.4
	Geopolitical issues	Challenges associated with geopolitical issues.	6.7

Market risks

Table 4.10. Market risk descriptions

Type	Source of risk	Description	% of farms
External	Price risk	Misestimating the market price of the product to be sold.	6.7
	Commercial risk	Excess supply without enough customers	3.4
	Competitor risk	Comparable products at a lower price or higher quality results in lower market share.	10.3
	Supply chain risk	Unable to source certain supplies or receiving damaged consumables.	13.1
	Customer withdrawal	A customer retracts their purchase order.	3.4
	Customer complaint	Customer complaints tarnish the reputation of the business.	3.4

None of the risks described are specific to VPF. However, the weighting of risks compared to traditional agriculture lies towards labour, finance, production, and technology instead of the environment. VPF leans more heavily towards financial risk due to the required capital and operating costs. There is also a trade-off because an IVF can operate independently of the natural environment and loses the buffer that nature provides, requiring constant control. Any problem in an indoor environment is likely to be magnified as it affects the entire operation. Technology plays a more prominent role in growing crops, introducing more points of failure throughout the entire operation. 33.6% of operators reported equipment failure, which could hamper crop quality and have high repair costs. Labour issues, predominantly human error, were the most commonly reported risk (53.3%) and could result in 100% crop loss due to an accident like incorrect dosing of nutrients or pH. Similarly, pest outbreaks and physiological disorders have led to crop failure. Electricity price is the largest risk at this point in time for many operators, however the interviews were conducted over the course of several years before the coronavirus pandemic until after Russia's invasion of Ukraine which has indirectly increased global energy costs. Therefore, the risk of electricity price increase did not affect most farms at the time of interviews.

Profitable farms attributed some of their success to a good understanding of risk management and conducting a risk register before building their facility. Long-standing operators said that after running IVF for several years, many of the problems arise. Specifically, after 5-10 years when LED lighting requires replacing and many farms are not designed for ease of maintenance.

The risks are interconnected and can affect one another. For example, a pest outbreak may result from improper growing conditions due to a HVAC failure. Technology advancements could result in a competitor risk with higher unit economics and better plant quality. A geopolitical crisis may increase the electricity price. Figure 4.18 shows the interconnectivity of the main risks detailed within this study and how they connect. Further investigation is required to determine the risks of the greatest concern.

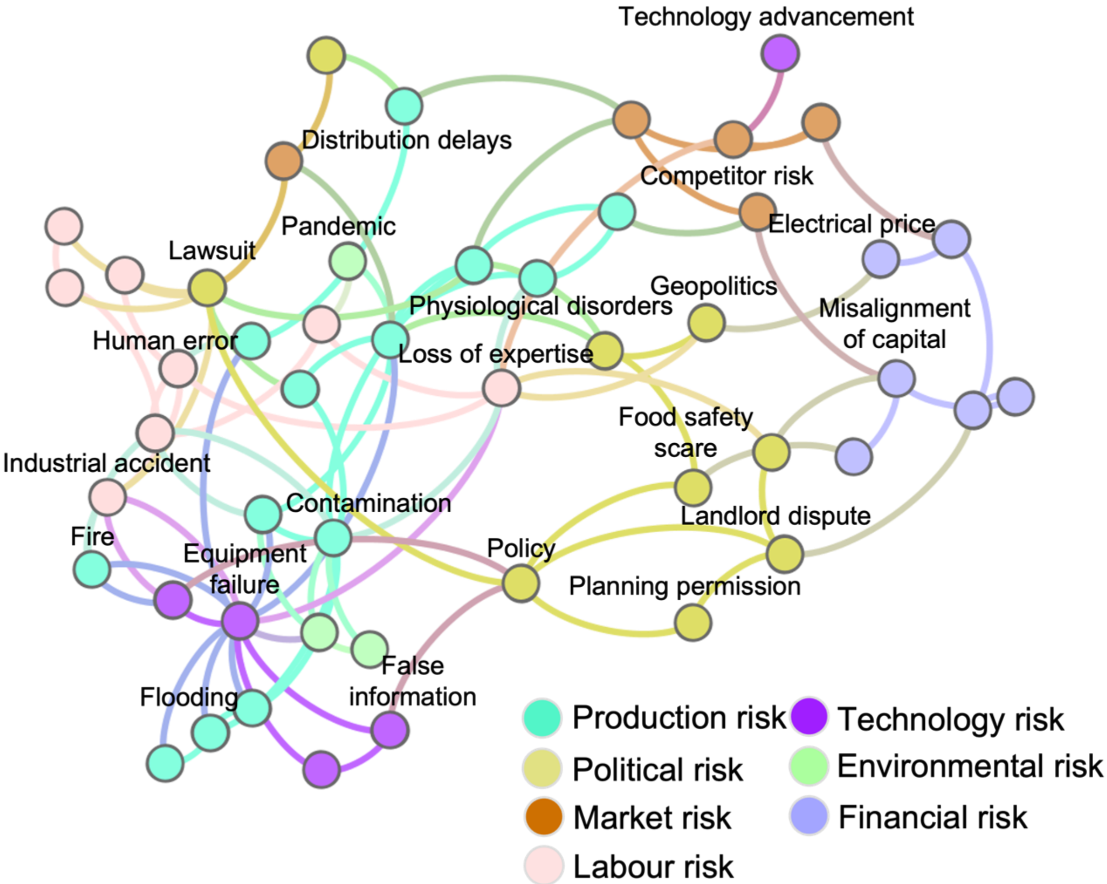

Figure 4.18. Risk interconnections map.

Failure Modes

VPF is operationally complex, and there are many potential modes of failure. The failure rate is high, yet there is no data for the number of vertical farms globally, let alone the failure rate. Even as VPF technology and production advance, the sector suffers from a knowledge gap which forces operators to seek information from outdoor growing practices or greenhouses. This study draws upon the experiences of 9 shuttered farms (47% of the farms examined) and three consultants to understand failure modes. Figure 4.19 diagrammatically represents the reported causes of failure alongside indirect causes.

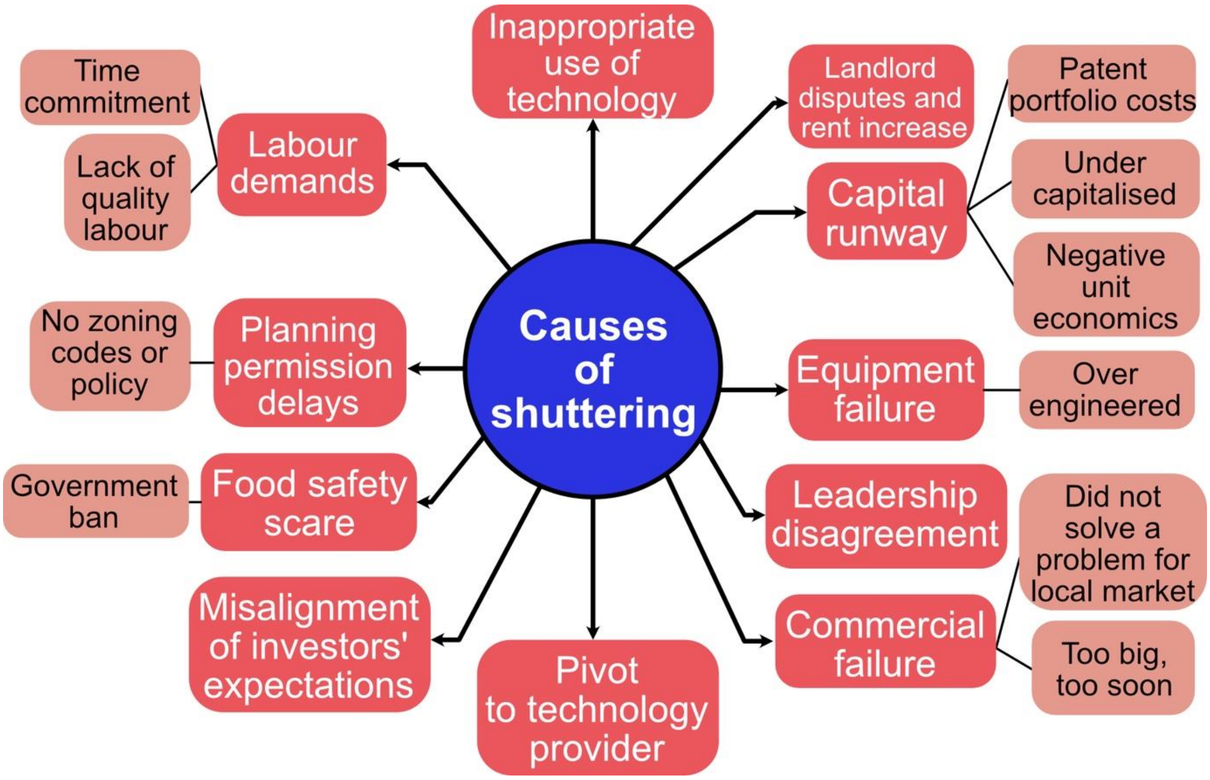

Figure 4.19. Modes of failure reported by farm owners.

The most common modes of failure were related to funding (70% of closed farms). Either farms were undercapitalised and at risk of not raising further funding or misaligned between investors' expectations and project goals. Due to unfavourable unit economics during the development cycle, farm owners could not bootstrap a business and required sufficient capital runway. As a result, they are dependent on capital investment (as described in Section 4.4.1).

The second highest reported failure mode was due to labour, or lack thereof. Farm owners struggled to find skilled labour to sustain their operations and could not provide the time commitment required themselves. This resulted in the shuttering of two farms and prohibited the scaling of others.

Another element in failure was building an ambitious project without first conducting a pilot to find a product-market fit. Big projects that have not validated the business model and technology at scale seem to run into costly obstacles that are difficult to overcome once decisions are locked in place. Some systems were overengineered, which can have higher failure points and, therefore, more repair costs that bankrupted a farm. According to one consultant, inappropriate technology use was the most frequent cause of failure that they had witnessed. In other cases, they experienced commercial failure with insufficient demand to justify their business case.

Unforeseen planning permission delays due to a lack of zoning codes can also hinder the development of farms. In one particular case, environmentalists protested against constructing a multi-tier farm resulting in a 4-year delay in construction. In addition, the lack of government awareness has been detrimental in other ways, banning certain crop sales due to a food safety scare that meant one farm had to close down operations entirely even when VPF was unaffected by the risk. Other challenges that were reported but are not unique to VPF were: leadership disputes, rent increases, commercial failure, and founder burnout due to operational complexity and opportunity cost.

4.5 CONCLUSION

The VPF industry is uniquely placed to disrupt the distribution methods of the perishable produce industry and can provide unique benefits (high-quality, consistent, and local produce with no pesticides). Given its potential as a secure and sustainable source of fresh food, vertical farms are rising globally. However, there are many challenges that VPF has to overcome to become mainstream, and there are learnings from many dissolved projects. This study analysed combined experiences from 20 VPF practitioners and 10 secondary sources through mixed-method thematic analysis to investigate lessons learned.

Growing factors and how they interact are nuanced, and there was a lack of understanding amongst operators about addressing the limiting factor. This is compounded by the lack of knowledge around crop growth recipes, with many farms having to develop their own through trial and error. Literature and guidance on how to approach addressing the limiting factor are needed. VPF is capable of higher food safety measures from being in a controlled environment, unaffected by external food safety issues from soil-based agriculture. Many operators do not meet this potential, primarily due to a lack of understanding, guidance, and literature. This is a crucial element to address so that VPF is taken seriously.

The experiences highlighted the still-experimental nature of the practice, where almost all practitioners had to engage in R&D alongside commercial growing resulting in a high cash burn rate. Profitable farms were careful to limit their R&D efforts in terms of space and finance. Some decided to become technology developers solely because the technology was advancing too quickly to remain competitive as commercial growers.

The precise control of IVF and rapid crop cycles enables the transfer of scientific findings between academia and farms, which removes an obstacle in greenhouses and open-field farms. However, data aggregation requires collaboration amongst farms to develop standardised metrics and definitions. Definitions have been presented which now need to be integrated into business operations [16,357]. More metrics and indices are sorely needed and will accelerate R&D, avoid the need for duplicative efforts, and eventually enable growers to focus primarily on growing solely.

Energy efficiency and automation are two vital areas for improvement. Moreover, VPF technology may not always be an appropriate choice, and operators should carefully analyse the selected product's CapEx and OpEx requirements relative to other growing methods. Finally, they should prioritise listening to their target customer, solving a problem for them by using technology. If they choose to create an entirely new product not available elsewhere then they will need to invest capital and time to build the market which opens a business to substantial commercial risk.

The most significant barrier for VPF was funding, and to substantially contribute to agri-food supply chains, the set-up costs must come down. Vertical farms are capital-intensive, and because of this, investors expect significant profit margins and cash flow. Therefore, it is essential to communicate the reality of VPF to acquire suitable types of investment. Producing an operational history showing continuous improvement and reducing volatility alongside unit economics and a large total addressable market are steps that can help when seeking funding.

Labour was another primary challenge for farms. It was the highest cost for all the farms involved and was the most frequently reported limiting factor in production. VPF was most susceptible to labour and technology risks, whereby one mistake from an employee could result in crop failure for the entire farm. It is important to design a farm and processes that are not dependent on an individual's competence to avoid such accidents. Compared to traditional agriculture, where the environment provides a buffer but is also the primary source of risk, VPF appears to magnify labour and technology risks substantially. A competent and experienced team in food production is helpful to mitigate this. Improving process flow through tried and tested methods of manufacturing principles could be vital to improving profitability and reducing risk. Further work is required to apply these principles in an indoor farm environment.

The study is limited by a relatively small sample size across leafy greens, herbs, microgreens and edible flowers. Further investigation is required amongst larger-scale producers and other produce such as plantceuticals, mushrooms, berries, transplants, fodder, etc. (as described elsewhere in the book).

This study is the first to examine and report risk factors and failure modes for VPF and was conducted in conjunction with a financial risk assessment study [75]. However, further work is required to engage VPF operators to prioritise and rank risks to evaluate likelihood, impact and mitigation measures. In addition, longitudinal production data will enable more precise financial and risk estimation.

4.6 GUIDELINES

Economics

- Seek subsidised or free rent and utilities from a sympathetic landlord or governmental subsidises where possible.
- Create alternative revenue streams to buffer the farm from dependence on sales.
- Find a patient funding provider with aligned expectations to the project's goals.
- Account for depreciation and repair costs in projections.
- Raise enough capital to allow for commissioning and experimentation phases.
- Estimate financial projections with validated data and add contingency margins on yield, waste, and costs.
- Purchase the maximum possible light efficiency at the best value when purchasing lights.
- Consider a 50-200 m^2 facility for the retail market or a 1000-6000 m^2 facility with modularised cultivation rooms for the wholesale market.
- Labour is the highest cost, and estimations should account for challenges, workflow bottlenecks, and slower working speeds (see Section 4.4.2).
- Calculate unit economics and tie them to customer sales to drive decision-making.

Labour

- Hire a team with food production experience and predominant skills in horticulture, engineering, economics and marketing.
- Hire or outsource knowledge in food safety, manufacturing and plumbing.
- Pay over minimum wage with incentives to improve labour satisfaction and engagement.
- Hire flexible labour for peak work periods.

- Apply manufacturing principles to improve the process flow of the farm [see [205]).
- Cultivate connection between management and growing teams.
- Consider accessibility, maintainability, and repairability of the farm and systems.
- Purchase automation only when necessary (see Figure 4.8).

Growing

- Create a strategy for identifying the limiting factor that considers all interconnected growing factors in Figure 4.11 and Table 4.3.
- Ensure proper food safety practices to minimise contamination risk.
- Avoid building a farm whilst operating it unless wanting to pivot into technology development.

Technology

- Conduct trials and ensure appropriate technology selection that combines competitive plant quality and economics.
- Select the technology by reverse-engineering from the crop and the customer.
- Measure net yield (kg/month), unit economics (£/kg), and crop productivity per unit of energy (kg/kWh) and labour (kg/man-hour).
- Have a deliberate data collection and action strategy to build the foundation for machine learning for managing growing factors.
- Create an operational history of yield per crop type since starting the farm, ideally showing increasing performance with reducing volatility to help seek funding.
- Enhance agility with flexible systems like DFT and mobile racks, especially for smaller farms.
- Keep systems simple and avoid overengineering the facility, focusing on the customer and the crop type.
- Consider accessibility, maintainability, and repairability of the farm and systems as critical criteria.
- Bring in a HVAC expert with experience in indoor horticulture to properly size requirements.
- Integrate systems early with an experienced farm designer or connecting systems will require substantial cost and time.

Strategy

- Start with a pilot to validate the technology and business model.
- Select and prioritise the values and goals of the business with the 80/20 rule.

- Create a backup plan.
- Build collaborations with academia, system suppliers, location partners, and other farms.
- Choose a site with characteristics shown in Figure 4.16.
- Place the farm in the right area relative to the customer (see Figure 4.17).
- Form a unique pricing strategy based on the value of VPF produce.
- Secure a growing contract to reduce waste and insure the crop.

Risk

- Create a risk management plan before building a PFAL to avoid knee-jerk reactions and costly mistakes based on Section 4.4.6.
- Consider the common failure modes and strategies to mitigate these challenges.

ETHICS STATEMENT

The study received full ethical approval from the Liverpool University ethics committee. All participants provided informed verbal or written consent to participate and were advised that they were free to withdraw if they wished to do so. All interviews were recorded with participants' permission and responses were anonymised.

CHAPTER 5

LEAN PRINCIPLES IN VERTICAL FARMING

FRAMING

Labour was identified as the top challenge by controlled environment agriculture (CEA) and vertical farming (VF) growers in the widest-reaching industry survey in 2019 [61]. Labour includes skills, ability to work with technology, productivity, and overall labour cost. Moreover, a conference panel from shuttered farm operators emphasised the importance of manufacturing principles when designing and improving a facility. This aspect of operations is a limiting factor for economic viability, and the interview study highlighted the impact of poor process flow design. Despite this, labour efficiency is highly under-researched in CEA and VF. One book chapter mentions the plan-do-check-act cycle, kaizen, and floor layout [113]; however, further work is needed to demonstrate the doubling of labour efficiency improvement that researchers and practitioners claim is possible [201]. The application of manufacturing principles was identified as an aspect to be included in the knowledge base of the DSS in Chapter 3 and a high-impact area of research to improve unit economics.

This chapter explores the use of one manufacturing systems method, lean manufacturing, to improve labour productivity and sales in a vertical farm. The authors explore the fundamental principles of lean manufacturing and apply them to a case study, Farm Urban's underground semi-closed-PFAL, describing before and after interventions. As Farm Urban was the industry partner for the PhD project, it was possible to work closely with their operators to collect process flow data and use their farm layout. This project exposed the void in the academic knowledge base and has been continuously applied by the case study farm since. Moreover, external operators who have read this research have implemented the principles described and found them helpful and practical. However, many VF systems are unpractical and have not considered ergonomics to access, maintain, and repair systems. I hope this work lays the foundation for further work to improve the labour productivity of VF configurations.

The study uses the term vertical farming instead of vertical plant farming, as it was written before the completion of Chapter 2. However, the findings relate to any kind of VF design.

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The contributions of the authors are the following: F.B.D.O conceptualised the research idea, F.B.D.O. generated figures, F.B.D.O. conducted experiments, F.B.D.O. designed the methodology, F.B.D.O. H.F. investigated the research area, F.B.D.O. wrote the paper, and F.B.D.O., H.F. edited and reviewed the paper, D.S., J.M.S. reviewed the paper, D.S. supervised.

Hannah Forbes, Dirk Schaefer, and Jelena Milisavljevic Syed individually consented to the use of this publication within this thesis.

LEAN PRINCIPLES APPLIED IN VERTICAL FARMING: A CASE STUDY

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5.1 ABSTRACT

Vertical farming (VF) has been recognised as an important tool for managing future food security, yet economic viability poses a significant hurdle with the majority of farms closing within three years. The application of lean principles poses an opportunity to address inefficiencies, such as significant labour expenditure, but existing literature is yet to consider process improvement methodologies in VF. In this paper, an established framework for lean implementation is applied to an industry case study providing techniques for process improvement. This work is novel and crucial for workflow standardisation and higher profit margins in this emerging sector.

5.2 INTRODUCTION

In this introduction, vertical farming (VF) and its challenges are presented, followed by a selection of an appropriate process improvement methodology and the research aims.

5.2.1 VERTICAL FARMING

VF is a method of food production that uses the vertical dimension to grow crops hydroponically, typically with indoor controlled environment agriculture (CEA) technologies such as artificial grow lighting [38]. Over the past decade, VF has seen a surge in popularity [44,61] and it is viewed by many as a method to engage with a plethora of global challenges facing food production such as the growing population, water scarcity and food safety [33,38].

VF involves the management of highly complex systems and, despite the opportunity it presents, standard approaches to process management are yet to be adopted in the industry. Addressing this knowledge gap could resolve several issues currently facing the industry. Economic viability is one of the core obstacles facing this sector [146], as start-ups have struggled with (i) underestimated labour costs [78], (ii) lack of adequate VF knowledge and education [78] and (iii) inefficient workflow and inadequate ergonomic design considerations [77,78]. In the largest survey conducted on CEA businesses globally in 2019 (n=316), human labour was identified as the largest challenge for growers [61]. Industry reports indicate labour is the single highest operating expense for even the most well capitalised vertical farms [61,62], accounting for roughly 56% of a vertical farm's operational costs (n=45) [62]. Solutions to this key issue are likely to lie in the processes adopted for the management of the farm. Practitioners have begun to consider manufacturing methodologies but techniques have yet to be discussed in the literature.

Securing funding and scaling are other core issues experienced by the VF industry identified by the CEA Census [61]. Both issues, as emphasised by industry experts [358], can be addressed by considering good process flow. The increasingly manufacturing orientated nature of high-tech indoor farming allows the application of systematic methodologies, such as lean manufacturing principles. Moreover, the reduction in supply chain from the majority of vertical farms located near the point of consumption results in farms performing a wider spread of value-added activities (i.e. processing, packaging, marketing and delivery). This makes VF a good candidate for methods that optimise value-added systems.

5.2.2 Why Lean Manufacturing for Vertical Farming?

Applying process improvement methodologies to support the standardisation of processes in VF could support the industry in overcoming the aforementioned challenges. As VF achieves drastically reduced harvest times compared to traditional farms, it has potential to benefit from manufacturing methods. However, despite numerous VF practitioners stating the implications of considering such methodologies [358–361], the literature on the subject is scarce. The most significant writing is a book chapter called "Plant Production Process, Floor Plan and Layout of Plant Factories with Artificial Lighting (PFAL)" [362] (PFAL is the Japanese term for vertical farms). The chapter briefly discusses application of principles of motion economy at a relatively high-level, requiring further discussion for contextual recommendations. Without literature to develop on it, it was therefore necessary to consider which process improvement methodology could be most useful in a VF context.

To determine which methodology was most appropriate to consider first, several methodology selection frameworks were considered. These were used to compare Six Sigma, Lean, Total Quality Management, Just-in time (JIT) and Agile as outlined as the key methodologies [363]. Some frameworks [364] demanded too much detailed data for selection. A rigorous selection process of this kind was not appropriate for a new industry where key metrics such as product output, capacity and power are not yet standardised. Two higher-level frameworks were then consulted [365,366] which both suggest that new industries "in the absence of regular, consistent and standardised output" should consider lean manufacturing principles which emphasises reduction of waste of all kinds. For new industries, key product indicators are still being standardised and the chosen methodology must consider much more than the product output. In support of this suggestion, Garvin [367], states that if the operations in general rely on shop-floor employees as opposed to automation, methodologies that focus more on the reduction of waste as opposed to defects and product flow, should be used. The vertical farming industry in general is gradually introducing automation but most farms in the United Kingdom are currently predominantly operated by shop floor employees [69]. Finally, single cell operations or those with limited product variety, which currently represents most VF operations should aim to adopt lean principles [364]**.** Lean manufacturing was therefore chosen among other process improvement methodologies to explore first in context of vertical farming.

Lean manufacturing methods can improve process flow in manufacturing environments, reduce fatigue and eliminate unnecessary movements through highlighting processes that add value and reducing everything that does not add value to the customer. Through streamlining operations and implementing "poka-yoke" mechanisms, to avoid human mistakes [368], labour risks can be reduced and profitability of VF projects can be improved.

5.2.3 Aims and Objectives

In this paper, the authors demonstrate the application of lean manufacturing implementation in the context of VF in a practical manner. This is the first work in academic literature to apply manufacturing principles to the nascent sector.

Core lean principles are analysed and applied to a case-study farm in Liverpool, United Kingdom. This is representative of many VF companies because of the limited variety of equipment solutions. With this paper the authors aim to enhance lean transformation for VF companies through the examples provided. To fulfil the aim of this paper, two objectives were developed:

1. To investigate lean manufacturing implementation methods
2. To evaluate how lean principles can be applied within a VF context through a case-study for practical implementation

The structure of the paper is organised into five sections. After the introduction, the second section describes and illustrates the case-study and its existing operations. The third section is broken down into three lean manufacturing principles and how each can be applied to VF (with an example for the case study). The fourth section consolidates the considerations improvements in operations for the case-study. The final section concludes with the potential implication of implementing lean principles proposed, addressing the research objectives and providing recommendations for future research.

5.3 Case Study: Liverpool Crypt Farm

This study was done in collaboration with Farm Urban [167], utilising their 200 square-metre vertical farm located in Liverpool as a case study to provide empirical recommendations. Situational analysis was conducted to assess the organisational attributes such as personnel, facilities, location, products and services to discover opportunities to apply lean principles. Figure 5.1 shows the initial state diagram for the existing layout and operations.

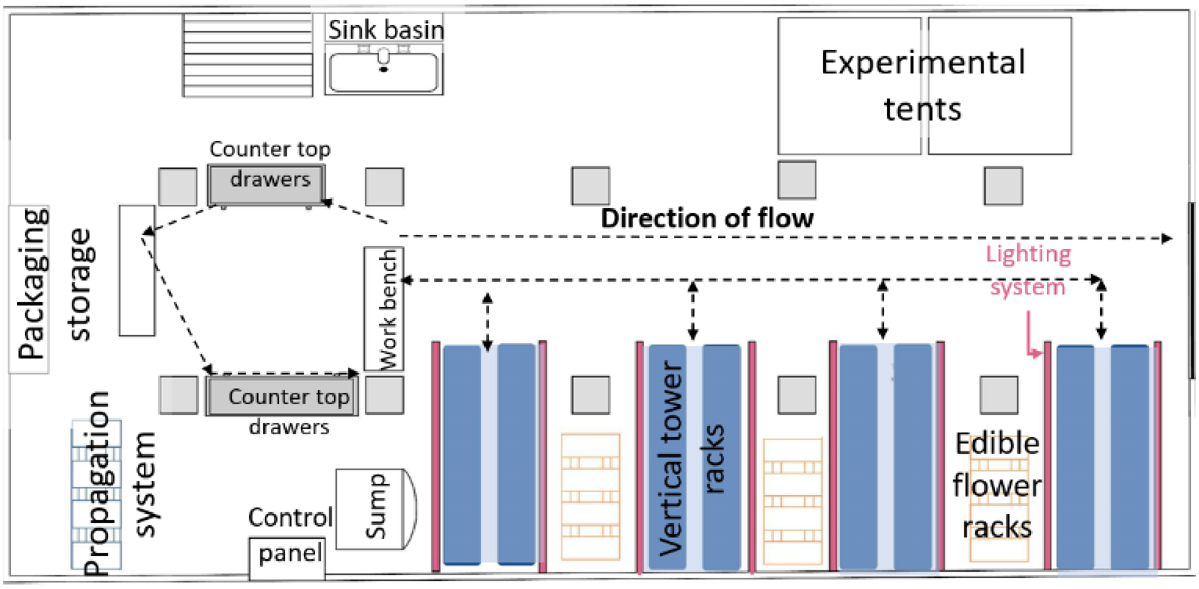

Figure 5.1. Initial state diagram of Liverpool crypt farm layout.

<u>Facilities and Location</u>: The farm is based in a basement in Liverpool city-centre. The farm has a production capacity of 200 kilograms of leafy green salads per week using mobile vertical tower growing systems (240, eight-foot towers), complimented with four-tier rack systems for edible flowers. Nutrient dosing and climate control have been automated.

<u>Personnel:</u> The farm is run by four employees. An operations manager, a master grower and two farm hands.

Operations: The farm is in the comissioning phase and standard operating procedures (SOPs) are under development. Protocols are being managed weekly. Performance metrics and standardised quality checks have yet to be implemented.

Product and service: The sales model is fixed-price and subscription-based. The product offering is a cardboard box containing four live heads of lettuce and a sealed jar of edible flowers delivered by foot within a two-mile radius.

5.4 Lean Principles Applied to Vertical Farming

Womack and Jones defined five process-orientated lean principles to eliminate the wastes providing a framework for lean implementation [369]. These principles are *Identify Value*, *Map the Value Stream*, *Create Flow*, *Establish Pull* and *Seek Perfection* [369]. In order to meet the scope of the paper we emphasise the exploration into three principles: *Identify Value*, *Map the Value Stream* and *Create Flow*. We excluded *Seek Perfection* as this principle relies on the implementation of previous principles for further improvement. *Establish Pull* has been excluded because, at this stage, consumer buying habits in the industry are unclear and building an improvement approach around inconsistent product demand is likely to result in inaccuracies, although there are examples of companies incorporating this concept [370]. Each principle is introduced alongside the relevant context in VF and explored.

5.4.1 Identify Value

Value represents the actual and latent needs of the customer that the business is fulfilling. A clear value proposition that defines a problem being solved for the customer is vital for commercial success. Identifying value is the first step in ensuring manufacturing processes are optimised for fulfilling customer needs. In this section, the process adopted by Pattanaik and Sharma (2009) for identifying value for lean processes is applied. It is first necessary to consult potential and existing customers in order to define value from their perspective [371]. There are many techniques to determine what customers find valuable, such as surveys, interviews, demographic information and web analytics [371]. In the context of Farm Urban and VF, key questions for identifying value are as follows:

1. What crop do the customers want?
2. How much do they want?
3. How do they want it delivered?
4. How much do they want to pay?

Each question covers a key aspect of the value-adding process, ensuring value is identified in the context of all key activities. This information is then used to identify how the existing offering can be optimised to meet customer needs.

For example, in the context of vertical farming, once a price point has been established (q. 4), this information can allow the crop selection to be optimised to ensure profitability. The use of metrics to address performance measures, targeted improvement and team recognition is inherent in lean [372]. Crops and practices that earn money should be tracked, and that which drain resources can then be the target of reduction and elimination. An easy way to do this is to track the value per harvest for each crop or the value per tray/tower. This is calculated by the number of crop per tower, the selling price and then deducting the associated costs of inputs: energy consumption, fertiliser, seeds, labour and maintenance.

Initial identification of value should lead continuous improvement in processes according to customer value [373]. If the customers are not retained, it is essential to determine the reason for cancellation. For example, it could be uncovered that the cardboard boxes are too large and are not valued by the majority of customers, in which case the box becomes representative of waste and over-processing and should become a target for reduction and experimentation. The identification of value and the optimisation of value is summarised in Figure 5.2.

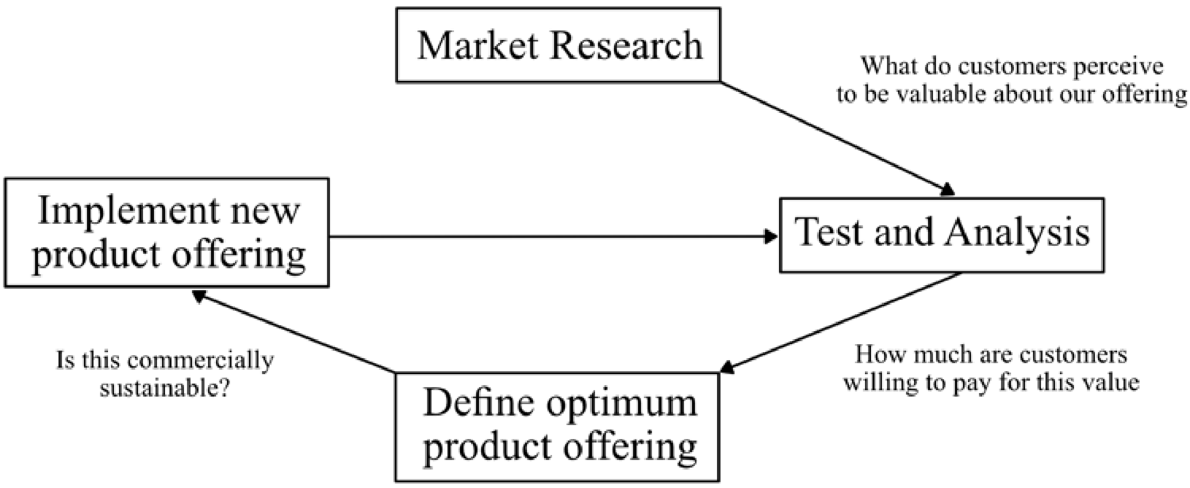

Figure 5.2. Identifying and optimising value in a vertical farming context

5.4.2 Map the Value Stream

Having described the process for identification of value, value stream mapping (VSM) is the next step in waste reduction [369]. This method is used to investigate processes by identifying value-added and non-value-added activities in the form of a diagram to understand how value flows through an organisation. While it is difficult to remove all non-value adding activities, increasing time spent on value-adding activities, is one approach to increasing efficiency according to customer value [373]. The output of a VSM exercise is outlining the process steps of each of the business: production, research and development, marketing, etc. These maps are vastly cross functional and vary in complexity [371]. To create a VSM this series of steps should be followed with the help of an experienced lean practitioner [374]:

5. Identify a product or service to improve
6. Bring together an experienced team
7. Decide the problem (lower price or increase in quality?)
8. Bound the process (limit the scope to an area which will have the largest impact)
9. Map the bounded process and define the steps
10. Collect and note process data
11. Create a timeline of the process with data
12. Assess the VSM current map and identify bottlenecks
13. Design a future map that aligns with the company vision
14. Implement future map and use it to communicate changes

VSM has been applied to the case-study to analyse harvesting, packaging and delivery functions of farm operations. This has been captured in Figure 5.3 as a simplified value-added flow chart. The exercise highlighted the inconsistency in time per activity due to a lack of standardisation as well as a clear need to reduce the number of quality checks and capture process data through timing activities. There were two bottlenecks identified outlined in red in Fig. 5.3: arranging packaging supplies and repeating batch quantities. This can be improved by introducing metrics and 'visual controls' such as signage for

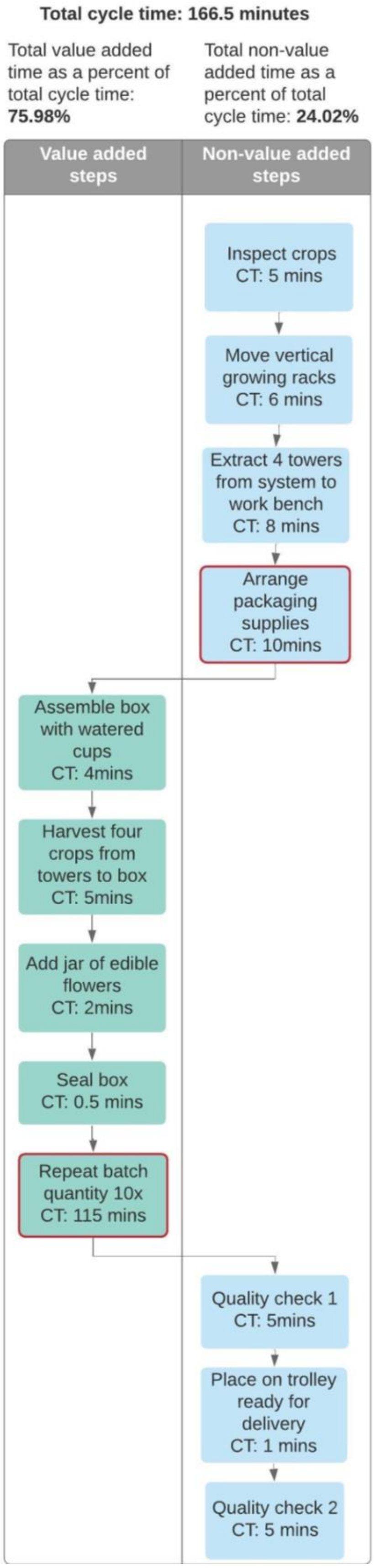

Figure 5.3. A value-added flow chart for harvesting and packaging processes.

acceptable product quality. By combining identification of value and VSM, insights can be gleaned from this customer focused approach.

5.4.3 Create Flow

Flow is a core concept in lean manufacturing, as any type of waiting is a form of waste. Creating flow of value involves a smooth delivery from the moment an order is received to the moment the product is delivered to the customer. Bottlenecks are the main impediment to developing smooth flow and managers should seek to understand how work progresses, where tasks get stuck and understanding the causes for these obstacles.

Two key lean methods for reducing bottlenecks and their impact are the first-in-first-out principle (FIFO) [375] and one-piece flow [376]. In this section, each of these methods are considered in the context of the case study.

One-piece flow means products flow from workstation to workstation without waiting. The maximum product waiting in a work station is one, and according to Liker [377], this is the only production method which reduces all types of waste. The 'work cell' is a common way of implementing one-piece flow, whereby workstations are moved close together to minimise transport between them [376]. A U-shaped cell reduces the operator's movements substantially whilst allowing access for multiple workers. A farm should maximise the number of workers able to access a layout simultaneously whilst maintaining speed and ease of access to ensure efficiency. Figure 5.4 illustrates a U-cell configuration applied to the case-study for the packaging and transplanting area in Figure 5.1.

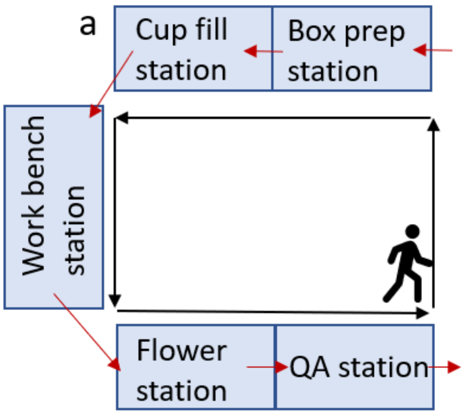

Figure 5.4. a) a U-cell with one operator b) a U-cell with two operators. Red arrows visualise the flow of product in the cell and the black arrows visualise the operator's movements ending at the quality assessment (QA) station.

FIFO is another method to create flow and manage inventory, by keeping inventories small and waiting times low. FIFO is the principle and practice of production by sequencing to ensure the first part to enter a process or location is also the first part to exit [375]. This has been used in all sorts of applications and is suited for managing perishable products within a short crop-cycle. In the context of VF, seedlings would be transplanted (pushed) into a vertical farming system. Knowing the crop type can be extremely beneficial in order to get the most out of this method, enabling the layout of a farm to be optimised for the various growth stages of a plant's lifecycle (see Figure 5.5).

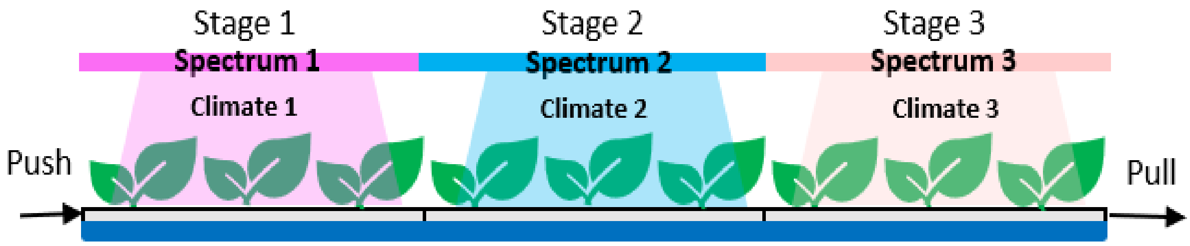

Figure 5.5. A diagram applying the FIFO principle to a VF system, where crops flow from one end through a sequence of optimised growth environments

A system with FIFO in mind would take a batch of seedlings through a sequence of environments optimised for plant phase development: germination, vegetation, flowering and production of secondary methabolites. It is then pulled out at the end, ready for harvest and delivery. There are many vertical farming systems available yet very few take advantage of this relevant and simple principle. Intravision's "Gravity Flow System" is one example of an automated system that utilises FIFO [378]. To make the most of FIFO method the ideal growing conditions or "crop recipes" are required. If conditions are not known, lean principles alone are unable to optimise this process, and artificial intelligence (AI) techniques have demonstrated its capacity in VF to optimise the input parameters for each crop. FIFO can and should also be applied to stock to reduce inventory risks.

5.5 Lean Development at the Case Study Farm

Identify Value, *Map the Value Stream* and *Create Flow*, have been considered for the case study. This has led to changes in processes and management which are described below.

Firstly, the identification of value is underway by collecting customer feedback and experimenting with various product offerings. The business is also beginning to collect economic data to determine the value per harvest of a rack to reveal crops that drain resources.

Secondly, the understanding of the value-stream has led to efforts to collect process data, map the whole value-stream and mitigate bottlenecks by avoiding batch processing. The value-stream mapping process revealed a significant bottleneck in the harvesting/packaging processes, primarily due to a lack of flow in resources, layout and infrequent quality checks resulting in rejected batches. The authors recommend to reorganise resources near to their point of use and implement clear visual controls to reduce frequency of quality checks. Data that is recorded digitally for traceability using spreadsheets is another bottleneck in operational flow and could be made efficient using a tailored enterprise resource planning tools. Visual controls are now being used to prompt corrective action according to the SOPs and to aid quality checks. Examples include: markings for placement/orientation of equipment during transplanting and harvesting of towers, as well as maximum and minimum indicators for draining and filling the sump tank. These initial changes have proven effective to mistake-proof processes, and now the farm will begin to integrate further visual controls for all of their SOPs. The process data, such as time taken per step, will be tracked by staff using stopwatches and added to SOP documentation with the goal to track continuous improvement. This process data will be used for a thorough value-stream analysis as the farm investigates further application of lean principles.

Lastly, the creation of flow has been incorporated by amending the packaging and transplanting area of the farm to be aligned with the U-cell layout in Figure 5.4. Suggested changes for shop-floor layout have been illustrated in Figure 5.6, adjusting positioning of racking systems to integrate the FIFO principle. Currently, this is not possible to implement due to fixed equipment, but this provides consideration for future developments with a fixed crop selection. The two racks kept in this formation allow for one or two crops to cycle through the growing climates. The U-cell layout has also been rearranged and moved closer to the entrance for the farm to avoid unnecessary movement into the growing area and to enable quicker delivery and lower risk of contamination.

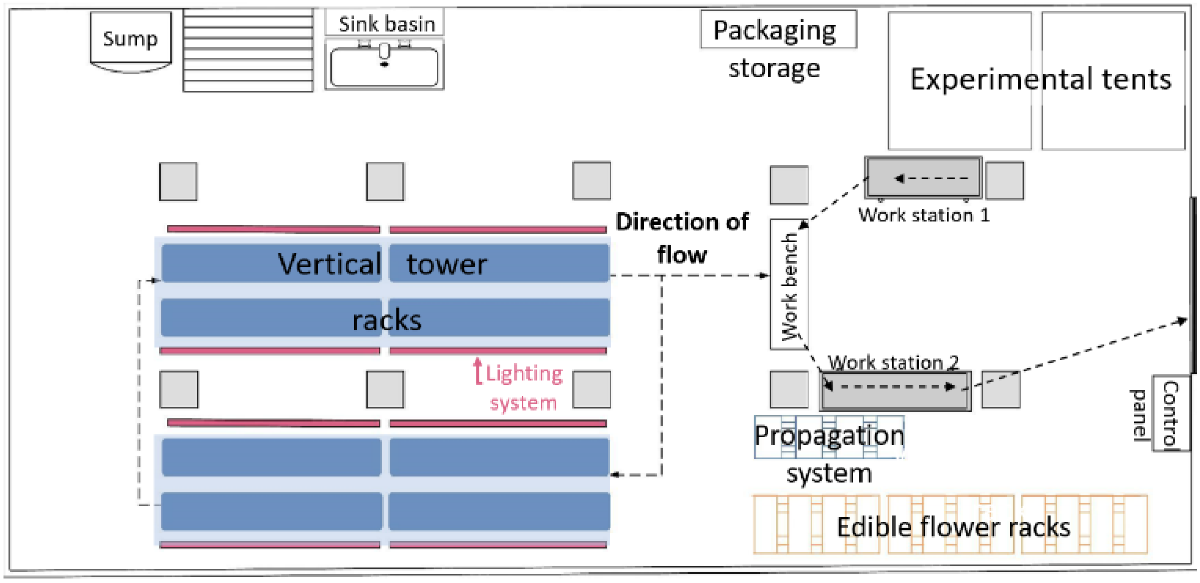

Figure 5.6. The post-improvement state diagram of case study cultivation area layout

5.6 Conclusions and Future Works

Vertical farming (VF) benefits from unprecedented control and rapid crop cycles that enable the implementation of manufacturing methodologies. While industry practitioners express the value that manufacturing methodologies could offer the industry [78], there is no available guidance or literature. After consideration of different process improvement methodologies for VF, the authors determined lean principles to be one way to engage with labour challenges reported in the sector [61,78]. This paper is the first of its kind to provide guidelines for implementing lean manufacturing principles in a VF context.

The authors have explored three lean manufacturing principles as described by Womack and Jones [369] and how they may be integrated into VF through the industry case study, Farm Urban [167]. The authors demonstrate the opportunity for significant improvements with minor adjustments to the farm, such as measuring time between value-adding activities to identify bottlenecks and reduction of non-value adding activities. Techniques have been explored to reduce: i) excess storage, ii) batch processes, iii) inefficient workflow and iv) crop cycle times. By applying FIFO principle, production scheduling can be made easier with quicker harvest cycles due to optimised growth parameters.

The complex and biological nature of growing crops requires "crop growing recipes" that lean optimisation methods alone are unable to optimise. This phase can be discretised into different grow-stages (as seen in Figure 5.5), however artificial intelligence (AI) techniques to optimise phenome, environment and resource inputs

[63] should be exploited if a farm wishes to rotate different crops. This is well recognised by practitioners, and is utilised to add-value through data-driven “crop growth recipes” [63]. Therefore, the authors suggest a hybrid approach of lean and AI for value-added system optimisation for VF processes with a flexible product offering.

As the VF industry seeks the path to profitability, key players utilising AI and automation to scale will find good process design and standardisation tools provided by lean manufacturing techniques. This can prime a business for scaling, proven by its track record particularly in the automotive industry [369].

This exploratory paper lays the groundwork for further lean principles to be considered. Exploring principles such as *Establish Pull* and *Seek Perfection* could provide guidelines for vertical farms to avoid over production, improve customer experience and consequently boost profits. In addition, several other manufacturing methodologies such as Kanban and JIT are likely to hold similar opportunities to the application of lean principles, and therefore should be explored in parallel. Work is currently underway to collect process data and integrate further lean manufacturing techniques to the case study farm to develop best practice guidelines and mathematical models which can be used for other farms. The authors hope the novel nature of this work in the sector will facilitate the adoption of process improvement methodologies, providing an agenda for further research by exposing voids in the knowledge base.

CHAPTER 6

FINANCIAL RISK ASSESSMENT MODEL

FRAMING

The adaptable economic viability and financial risk model proposed in the DSS framework in Chapter 3 is realised in this chapter. This was the crux of the PhD project and combined all the work that had been conducted into a prototype of the DSS. The interdisciplinary project required understanding finance, risk and uncertainty quantification, benchmarking data, and engineering. The prototype DSS created is an excel spreadsheet which allows users to make decisions about their vertical farm: system selection, crop type, currency, location, energy type, team salaries, etc. (the input list can be found in Appendix C). The data is processed through an open-source Python model, with modules containing yield projections, risks, systems, lighting solutions, environmental impacts, capital costs, and other default economic values. When executed, the model uses probability-bounds analysis to run all the possible simulations and provide financial risk assessment according to the user's needs. I applied the model to two case studies: a PFAL in the UK and a PFAL in Japan. First, I worked with my industry partner (Farm Urban Ltd.) to validate the model. As an industry partner, they provided production and financial data. I applied the model to their UK farm and then tested it on the hypothetical data provided in a book chapter by Uraisami (2018) [86]. The results are presented in this chapter. This is the first time risk assessment, or financial risk, has been applied to PFALs or vertical farms in the academic literature or the public domain. Moreover, the economics of indoor agriculture is still under-researched, and this study provides new methods to assess economics without data.

The study uses the term vertical farming instead of vertical plant farming, as it was written before the completion of Chapter 2.

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The contributions of the authors are the following: F.B.D.O. conceptualised the project, F.B.D.O. designed the project, F.B.D.O. programmed the software, F.B.D.O. developed the graphical user interface, F.B.D.O. validated the software, F.B.D.O. conducted the formal analysis, F.B.D.O. conducted the investigation, F.B.D.O. managed the resources, F.B.D.O. curated the data, F.B.D.O. wrote the paper, F.B.D.O., R.A.D.D., S.F. reviewed and edited the paper, F.B.D.O. visualised the results, F.B.D.O. managed the project. J.M.H.T., S.F., N.G. helped with programming, P.D.M., J.M.H.T validated the data of the case study, S.F., R.A.D.D. supervised and P.M. acquired funding.

Scott Ferson, Ronald Dyer, Jens Thomas, Paul Myers, and Nicholas Gray individually consented to the use of this publication within this thesis.

How High is High Enough? Assessing Financial Risk For Vertical Farms Using Imprecise Probability

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6.1 Abstract

Vertical farming (VF) is a method of indoor agricultural production, involving stacked layers of crops, utilising technologies to increase yields per unit area. However, this emerging sector has struggled with profitability and a high failure rate. Practitioners and academics call for a comprehensive economic analysis of vertical farming, but efforts have been stifled by a lack of valid and available data as existing studies are unable to address risks and uncertainty that may support risk-empowered business planning. An adaptable economic analysis is necessary that considers imprecise variables and risks. The financial risk analysis presented uses with a first-hitting-time model with probability bounds to evaluate quasi-insolvency for two unique vertical farms. The UK farm results show that capital injection, robust data collection, frequent cleaning, efficient distribution and cheaper packaging are pathways to profitability and have a safer risk profile. For the Japanese farm, diversification of revenue streams like tours or education reduce financial risk associated with yield and sales. This is the first instance of applying risk and uncertainty quantification for VF business models and it can support wider agricultural projects. Enabling this complex sector to compute with uncertainty to estimate financials could improve access to funding and help other nascent industries.

6.2 Introduction

Agriculture faces a plethora of threats including unusual weather phenomena, water shortages and ageing rural populations [32]. These combined challenges require innovation in resilient farming methods to meet the demands of a growing population. Vertical farming (VF) is one such method that may contribute towards food and nutritional security.

VF is a novel form of agriculture, defined as multi-layer indoor crop production systems with artificial lighting, in which growth conditions are controlled [19]. Plants can be stacked vertically (in towers) or horizontally (in trays or gullies) [19]. The goal is simple, to produce more food with less land. It utilises controlled-environment agriculture (CEA) techniques, such as hydroponics with growing-specific light-emitting diodes (LEDs). Figure 6.1 maps the spectrum of agricultural systems across two gradients in technology and exposure to nature.

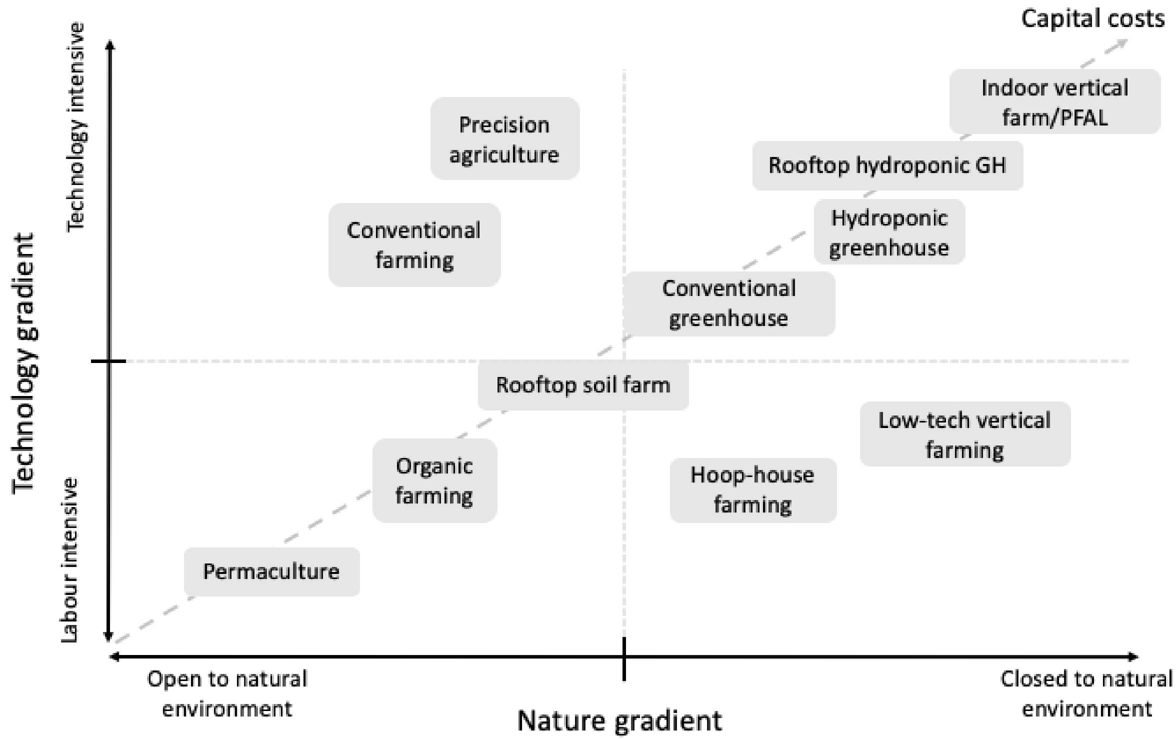

Figure 6.1. Spectrum of farm types (adapted with permission from C. Peterson & S. Valle de Souza [74]). Capital costs increase the further away a farm type is from the bottom left.

Indoor vertical farms, otherwise known as plant factories with artificial lighting (PFALs) [1], are typically the most technology-intensive and expensive. Consequently, they can control most growing parameters independently of external environment factors. This unprecedented level of control has enabled research to optimise production by fine-tuning variables, including light spectrum, temperature, and irrigation [104,379]. With such control, VF offers a host of advantages when appropriately managed, including higher yields all year round, quicker feedback cycles, longer shelf-life, and zero pesticide usage [32]. This form of agriculture can utilise the internet-of-things and big data to achieve smart factory performance [380]. The most popular crops to farm vertically are leafy greens, herbs, and microgreens due to high energy conversion to edible matter. Technically it is possible to grow any crop; however, economics and growing complexity constrain crop choice.

The industry has seen a surge of interest and significant investments in recent years [142,180,381], driven by advances in light-emitting diode (LED) technologies over the past decade. As a result, vertical farms are sprouting up worldwide, particularly in locations that make strategic sense (environments hostile to crops, regions with cheap electricity and markets for premium-quality food). The practice is not widespread and attracts scepticism. Criticism is focused on high capital and operational costs due to expensive equipment and the high-level expertise required to operate it, and high energy demands, which can result in low profit margins [19,115,382]. The learning curve is steep as the market, expertise, and technology begin to mature.

Market drivers are in VF's favour; however, there have been numerous failures over the past decade [146]. Continued investment is usually needed to sustain vertical farms; otherwise, they may bleed dry from negative cash flow [69,70]. Therefore, there remains hesitance to invest in VF [146,383]. A recurring complaint from investors, researchers, and practitioners is the scarcity of peer-reviewed research investigating economics underlying the construction and operation of VF [74,82,178,179]. Despite vertical farms operating in controlled environments and utilising data to optimise growing conditions, there is a lack of production, yield, and economic data available in the literature [82,146]. This is amplified by the absence of any standardised data framework and benchmarking. Variations in data quality due to complex climate controls and differing technologies, sensors, and yield measurement practices mean that data are not always applicable across farms. There are industry working groups now working towards standardisation [384,385]. The void of validated and peer-reviewed economic and risk data in the literature highlights a vital need for addressing the economics of VF so that it can be improved. One way to circumvent this is the utilisation of risk and uncertainty quantification techniques. In principle, risk management would reduce profit fluctuations and increase investments whilst raising farmers' income. As a consequence, improved access to finance could help with achieving sustainable development goals [386].

VF is a high-risk business, yet no efforts have been made to quantify and evaluate financial risk in the literature. There is a need to factor risk and uncertainty into business models for a more accurate assessment and to increase accessibility to funding [86]. This article explores whether VF economics can be analysed through a novel economic risk methodology, allowing imprecise random variables to assist farm owners and investors in making financially sensitive decisions. It aims to address the following research questions:

- How can farm economics be modelled with an absence of available production, risk and financial data to conduct economic viability and risk assessment?
- What is the risk profile for two case study farms, one of which benefits from a synergistic partnership with a landlord and cost deductions?
- How might a risk assessment tool be used to inform a profitable business model?
- The article is structured as follows:
- In Section 6.3, related works and their inability to accurately assess the economic viability of VF projects are discussed alongside potential risks;
- In Section 6.4, the model is proposed alongside the risk and uncertainty quantification methods, as well as the two case study farms;
- In Section 6.5, the results from the analysis are presented for financial metrics;
- In Section 6.6, the results are discussed alongside possible interventions to de-risk one case study, the implications of using the methods proposed in the broader industry, and the limitations of the analysis are discussed; and
- In Section 6.7, the conclusions are presented.

6.3 Related Works

In this section, the related works on the economics and risks of VF is investigated. Economic models on VF are grouped and then examined for their insights and challenges. Typical risks of the sector from VF and CEA are described.

6.3.1 Economic analyses

There are 16 disparate economic analyses from academic and commercial sources detailed in Table 6.1. The literature reflects the nascence of the industry.

Table 6.1. VF economic analyses alongside their characteristics.

Type	Source	Objective	Results
Cost analyses	[36]	Simulate the economics for a hypothetical 37-storey (167.5 m) vertical farm hybrid in Berlin, Germany.	Cost of production presented through probability distributions. Costs lie between €3.5–4 per kg in 44% of cases. No validation.
	[90]	Simulate life cycle costing for a hypothetical 50 m² apartment to study small and inexpensive VF.	Sensitivity analysis results indicate added value crops such as herbs and pharmaceutical ingredients are necessary for economic viability. No validation.

	[86]	Provide a business planning spreadsheet developed for a hypothetical 1000 m^2 PFAL based on expert's and industry practitioners' insights. Most comprehensive data set in the literature.	Cashflow projections for a profitable farm with a 7.8 payback period.
	[192]	Conduct feasibility study using central limit theorem to assess ROI for a hypothetical 5000 m^2 VF serving 24 canteens in Wuhan, China.	The breakeven on investment in this VF analysis is 11.5 years. Unviable crops are selected.
	[193]	Perform cost analysis for a hypothetical ZipGrow VF in São Paulo, Brazil comparing to Denver, North America, assessing its economic viability using vendor's data.	São Paulo provides a cheaper scenario in comparison to Denver, but possesses market conditions where low costs cannot compete with traditional farming product prices. Analysis predicts Denver as 14.17% IRR compared to −19.12% in Sao Paulo.
	[103]	Analyse the economics of a hypothetical six-story VF in Delhi, India, with a footprint of 200 m^2 and 3 stacked layers in each story.	Payback period calculated to be 64 years. Unviable crops are selected.
	[82]	Draw from hypothetical Japanese PFAL data [22] and substitute modern data in various scenarios (changes to scale, operations and market context).	Significant decline in capital costs, especially equipment (45%), make profitability increase substantially (ROI rose from 1.8% to 14.3%). Scale of operation is critical to profit as well and depends on the proportion of fixed costs in the operating structure. Doubling the size of the PFAL results in the enhancement of ROI from 14.3% to 22%.
Software systems	[76]	A flexible system for predicting costs and return-on the investment of a VF, with results shown for several hypothetical scenarios and sensitivity analysis.	Return on investment is sensitive to price of electricity, crop price and CO_2 concentrations. Software not publicly available.
	[84]	A commercial and flexible digital platform for economic estimation of farms, greenhouses and VF.	Capital expenditure, operating costs and yield estimates alongside 15-year projection. Not peer-reviewed or academically validated.
	[146]	Evaluate business sustainability using imprecise data techniques using ideas from [28]. The economic modelling contained within "How High is High Enough?" builds upon the framework and executes the first passage time risk analysis on two case studies.	N/A—No results presented.
Greenhouse vs. VF	[85]	Simulate a hypothetical scenario comparing profitability of growing lettuce in a semiclosed VF and semiclosed greenhouse near Quebec City.	Results show that the costs to equip and run the two facilities are similar with higher gross profit for VF.

	[91]	Simulate scenarios to compare hypothetical VF and greenhouse facilities under various financing schemes in Denmark.	Results show that regardless of financing scheme, the VF facility was much more profitable compared to the greenhouse, with high IRR rates and a payback period between 2–6 years.
Industry surveys and reports	[62]	Present results of a self-reported survey of 56 indoor vertical farms (primarily in the USA).	Aggregated data for OpEx breakdowns per and profitable crops
	[115]	Present results of the government census of a number of profitable Japanese plant factories with typical production costs.	Aggregated data for production costs and percentage of profitable farms in Japan.
	[42]	Present results of a self-reported survey of 190 indoor vertical farms.	Aggregated and self-reported data on profitability and revenue.
	[102]	Design and cost an economically feasible next-generation VF concept. A workshop of experts design and cost five hypothetical food modules with margins to account for uncertainty.	The resulting concept is broken down into estimated capital expenditure and running costs.

Records and financial data on vertical farms are scarce, and this is demonstrated by the fact that most of the analyses are based on hypothetical case studies. The farms in these studies range from skyscrapers [36,103,192] to more realistic warehouses [86] and small-scale operations [90,91]. The sector has been notorious for being closed, yet it is starting to shift due to the immense complexity of combining elements of lighting, plant science, engineering, policy, architecture, and sustainability [79,384]. Currently, VF studies commonly extrapolate data from greenhouse literature [76,85,91], estimate values [36] or utilise projections from vendors [18,193].

<u>Cost Analyses and Scenario Simulation</u>

These analyses discuss the categories of capital expenditure (CapEx) and operational expenditure (OpEx) alongside the methods used to compute productivity and profitability [36,86,90,102,103,192,193]. Most of these struggle to provide a balanced assessment of feasibility of the VF projects due to an absence of empirical data. The complex nature of combining architecture, agriculture and digital technologies in an urban food-water-energy nexus context makes accounting difficult. The most comprehensive dataset of a vertical farm is a hypothetical PFAL in Japan [86]. One recent study expands on this dataset to test various scenarios with an updated capital cost reduced by 45% due reduction in equipment costs (changes to scale, operations and market contexts) [82]. It reveals that doubling the production scale with the same fixed costs can increase the return on investment from 14.3% to 21.7% [82]. Moreover, profitability hinges on commanding a premium price point whilst reducing costs (such as electricity through LED efficiency) without sacrificing produce quality [82]. It concludes that scale of operation, reduction in capital cost, and innovations in improving yield and produce quality are critical to profitability [82].

Economic Estimation Software

Customisable analyses are necessary to accommodate various scenarios and user inputs, especially as datasets are hard to come by. Tools exist that aim to help entrepreneurs compare different locations, systems, and business models [76,146], but only one is available for commercial use [84]. As a commercial tool, it lacks the rigour of peer-reviewed yield values and does not currently allow the user to consider any uncertainty or risks. Moreover, it is a black box and is therefore challenging to critique. [76] is not fully functional but the model informed [146], which provides the framework executed within this study.

Greenhouses vs. Vertical Farms

There are mistakes that can easily result from hypothetical data. Two studies conclude that vertical farms are more profitable than greenhouses in certain conditions [85,91]. Upon closer examination, the values for space utilisations (defined as floor space dedicated to growing divided by facility area) are unfairly skewed in favour of VF for both studies. Space utilisations are typically 50% for VF [115] and 60–90% for greenhouses [212]. Thus, the studies are misrepresentative of real farms. If an analyst adjusts the space utilisations to realistic values, then greenhouses are more competitive then the results suggest. If it were possible to compute with uncertainty about these assumptions, then perhaps false conclusions could be avoided. Neglecting depreciation is another critical mistake, as a comparison study claims that vertical farms are more profitable [85] without consideration for depreciation of vertical farming equipment like lighting. Greenhouses may use supplemental lighting but they are not in-use for up to 16 h a day all year, and therefore depreciation will happen at a much slower rate compared to VF.

Industry Surveys and Reports

These are the three analyses utilising real-life farm data, albeit two are self-reported surveys without auditing and are aggregated across different farm types, making them difficult to compare [42,62]. Nevertheless, they collectively cover a dataset of 461 vertical farms and provide some overview statistics including the percentage of profitable vertical farms increasing each year [18]. Some also include the percentages of cost components [62,115] and a snapshot of the average labour (0.0155–0.03 people per square metre) and water required (an average of 1.69 litres per square metre) [62].

6.3.2 Cost Components

Three elements primarily drive CapEx comprising 80–90% of costs: lighting, racking and grow system, and building [18]. The production costs consist of three major constituents that account for 75–80%: electricity, labour and depreciation [18,63]. There is no analysis whereby all cost components are considered. To highlight the disparity between both the real-life and hypothetical data for OpEx and CapEx, [18] collates all the available information for fixed and variable costs. This collation shows that researchers frequently omit heating, ventilation and air-cooling (HVAC), depreciation and CO_2 enrichment. Resource data are speculative in most cases.

6.3.3 Uncertainty

To date, most of the analyses rely upon deterministic models to predict cashflows [84–86,102,103,188,193,206]. Scarce data have forced researchers to utilise uncertainty quantification techniques in order to bolster analyses and improve accuracy [76,90,192]. World-leading researchers in plant factories claim that a risk scenario approach would benefit the sector but would require industry-wide research and cooperation (involving horticultural scientists, farm operators, equipment manufacturers, etc.) [63].

Stochastic methods are utilised in several models, such as central limit theorem [192], scenario analysis [36,91], sensitivity analysis [76,90] and probability bounds analysis [146]. Sensitivity analyses determine that profitability is sensitive to electricity price, crop price, sunlight contribution, photosynthetic photon flux density, and LED fixture efficacy [76,90]. These factors highlight the importance of electrical efficiency and suitable sales models.

6.3.4 Limitations

The primary source of error is that many of these analyses utilise speculative assumptions without accommodating uncertain inputs. An attempt to calculate uncertainty would represent more realistic cash flow predictions, especially as projected yields and costs can be misrepresentative [69]. Researchers often overlook HVAC costs in most economic analyses due to their complexity. Additionally, labour is costly, and automation solutions like seeding machines, packaging machines, and nutrient delivery systems are popular solutions, yet no analyses consider automated systems in their cost breakdowns. Researchers and industry practitioners recognise the need for more detailed economic analysis that model all the variable costs to inform business models and financial investment [36,76,82,228]. Without this and the lack of proven business models, there is insufficient evidence to address criticisms regarding profitability.

Moreover, all of the analyses are for unique farms and production systems with differing levels of technology and operating with different economies, making performance not directly comparable.

The learning curve is a vital element considered in only two cases [84,146]. Farms can experience an improvement in yield and produce quality depending on growing experience, wastage and the optimisation of parameters [84]. This improvement should be tracked in future studies for validation.

No studies have addressed the fundamentals of microeconomics, such as maximising profit and average cost curves. This would enable the assessment of economies of scale and finding the 'sweet-spot' in terms of facility sizing. Access to real data would reduce epistemic uncertainty in analyses. A credible foundation for literature will then develop. Computational uncertainty quantification could compensate for lack of available data. Lastly, risks and opportunities can be applied. A tool that could achieve this can inform decision-makers of VF viability with confidence and avoid costly failures. Other limitations are discussed within a review [18].

6.3.5 Risks and Opportunities

The VF sector is littered with failed start-ups, some of which have been spoken about publicly [78,214] and many that go unreported. Reasons for ceasing trading include:

1. cash flow problems [37,69];
2. underestimated labour costs due to operational complexity [69,78,293];
3. lack of adequate knowledge and accessible education about the integration and operation of vertical farming systems (irrigation, lighting, plant science, HVAC and manufacturing systems) [69,78];
4. inefficient workflow and inadequate ergonomic design consideration [69,77,78];
5. low profitability margins [77];
6. sources of capital investment and the misalignment of support and expectations from funders [69,78];
7. zoning codes and regulatory obstacles [69,299];
8. equipment failures and associated repair costs [71,78]; and
9. poor early decisions around pricing, crop selection and location [78,146,242,269].

These failures are acute because of the high CapEx investments required. The economic analyses omit all these risks that may influence crop productivity, sales, and profitability [69]. No empirical data exists for the frequency and impact of such events in VF except for anecdotal reports [69]. On the other hand, the literature on risk analysis in greenhouses and field-grown agriculture is more mature [387–395]. The sources of risk range widely. As indoor farming climbs the technology and nature gradient (see Figure 6.1) its risks shift away from external environmental factors and towards production risks associated with technology. Table 6.2 identifies and ranks the likelihood for risks for field-grown produce, greenhouses from the literature and compares against vertical farms based on anecdotal reports [69,78].

Table 6.2. Risk identification and corresponding likelihood for vertical farm, greenhouse and field-grown produce (cf. [69,72,387,390,396,397]).

Risk Parameters	Risk Source	Indoor Vertical Farm	Greenhouse	Field-Grown
Yield risk	Weather conditions	Low	Medium	High
	Pest outbreak	Low	Medium	High
	Pathogen outbreak	Medium	Low	High
Production risk	Environmental control (malfunctioning HVAC)	High	Medium	Low
	Electrical outage	Medium	Low	Low
	Incorrect nutrient/pH dosage	Medium	Low-Medium	Low
	Irrigation (flooding, clogs)	High	Medium	Low
	Equipment failure	High	Medium	Low
Cost risk	Energy expense variability	Very High	High	Low
	Underestimated labour costs	High	Medium	Low
	Technology advances	High	Medium	Low
Labour risk	Poaching of staff/Loss of expertise	High	Medium	Low
	Accidental damage	High	Medium	Low
Safety risk	Fire	Low	Low	Low
Planning risk	Zoning codes	High	Medium	Low
	Change of lease agreement	High	Medium	Low
Market risk	Market competition	Medium	Medium	Low
	Local supply/demand situation	Low-Medium	Low	High

Economists model such risks according to probability distribution functions known to decision-makers [393]. However, in empirical analyses, researchers almost never know the true probability distributions [393]. Economists assume that decision-makers hold beliefs consistent with known probability distribution functions. Rather than assuming the exact distribution whilst lacking adequate data, imprecise data techniques are better suited for estimating this.

Innovations in the VF sector have arisen to address the challenges and improve unit economics in an increasingly competitive market. Therefore integrating opportunities are equally important to consider. PFALs in Japan report that cost performance can be radically improved by reducing production costs and increasing annual sales [35]:

- A 50% increase in sales is achievable within five years by adjusting environmental control setpoints, selecting better cultivars, improving the cultivation system and reducing waste [63].
- A 50% reduction in production cost is possible through improving labour and electrical efficiency [63]
    - Automation, process flow and human resource development can reduce labour costs.
    - A 50% reduction in electrical cost is attainable within several years through the intelligent operation of electrical systems, insulation, LED efficiency advancements [63] and load shifting [303].

Other opportunities such as new customer contracts, introducing new technologies and scaling plans are out of the scope of this article.

6.4 METHODOLOGY

This methodology is broken down into several sections:

1. The economic model containing its framework and assumptions to calculate cashflow forecasts and return on investment (ROI);
2. The risk and uncertainty analysis, which describes the methods used, why they were used, the risk profiling results and the risks that will be considered within this analysis;
3. The case studies and associated data for a real-life and hypothetical farm.

6.4.1 ECONOMIC MODEL

The economic survivability model is a flexible and robust means to conduct financial risk assessment by combining historical data with risk and uncertainty quantification to fill gaps in knowledge. This method is based on previous work [146]. The model functions through a series of modules that interprets inputs based on the local market, selected crops, farm characteristics, labour, consumables and more. The flow of tasks is illustrated in Figure 6.2.

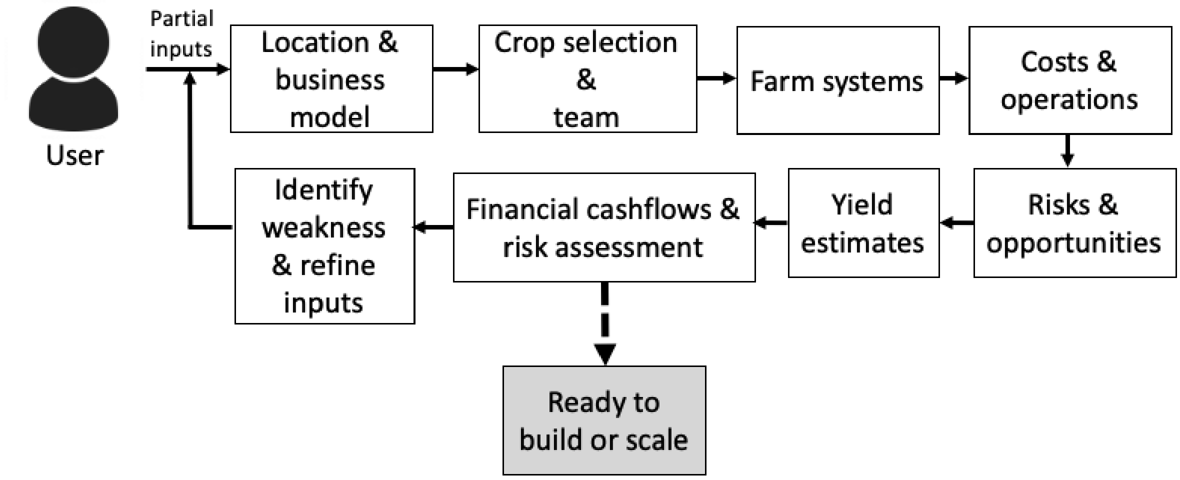

Figure 6.2. Flow chart of user interactions with model

The model computes cashflow forecasts and ROI based on either farm inputs or default values. Default values are estimated by decisions on location, system selection, crop type, farm size and other inputs based on the literature [146]. Once the inputs have been gathered, risk analysis is conducted using first-hitting-time, which will evaluate whether the farm is likely to fall under certain criteria in the future when accommodating for risks as well as reported opportunities. The novel application of probability bounds analysis enables the use of both complete and partial inputs where the specified farm (in planning or operational stage) does not have complete information.

Figure 6.3 shows the simplified flow of computation and cost components from left to right, whilst omitting the interdependencies inherent in plant growth. The model calculates revenues and costs such as CapEx, OpEx and cost of goods sold (COGS) for resulting ROI. To illustrate how the model functions to compute risk profiling, Figure 6.3 is labelled with numbers 1 to 12 corresponding to equations available within the Supplementary Method Statement (Appendix B). This information is collected through a series of spreadsheets before being processed by a Python script to apply uncertainty quantification and produce cashflows with risk profiles for quasi-insolvency. This is applied across all the potential scenarios based on user uncertainties, risks, and opportunities, relevant to the farm type. The resulting analysis is a 15-year projection for financial metrics and resource consumption, as the typical lifetime for a vertical farm is approximately 15 years [115].

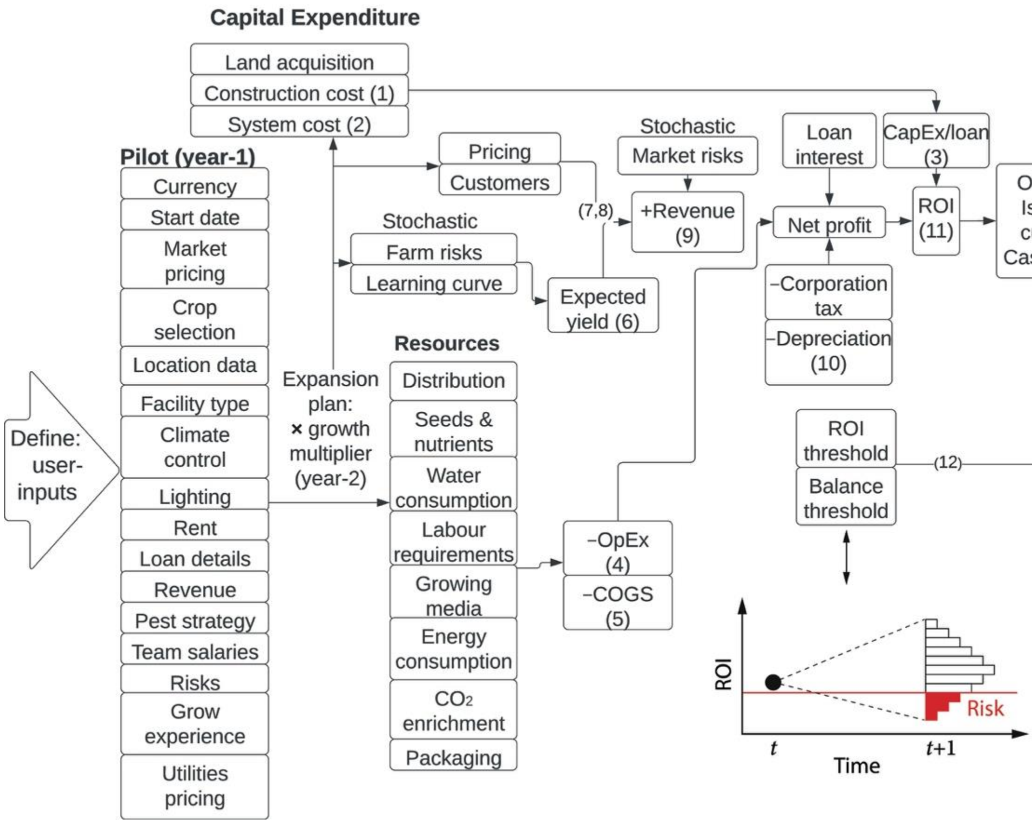

Figure 6.3. Financial risk model structure (flow left to right) utilising Equations S1–S12.

Refer to Appendix B for detailed breakdown of the model including its equations, assumptions and references.

6.4.2 Risk and Uncertainty Analysis

Stochasticity is included through random parameters such as failure rate, improved yields over time, repairs, infrastructural issues, potential pest or pathogen outbreaks and other risks. The user can also manually insert uncertainty for any parameter. How can these be accounted for if the distributions and values are unknown? Probability bounds can capture all information, even if there is only limited information available.

Probability bounds, expressed as bounds on cumulative distribution functions, are called "p-boxes" [398]. They can be used to characterise uncertain parameters, distributions, risks and opportunities without requiring overly precise assumptions [267]. There were other uncertainty techniques that could have been used instead, like Monte Carlo simulation or worst case analysis. However, this would require untenable assumptions, such as the uncertainties being small, the distribution shapes are known and the relevant science is modelled [399].

This is not the case, and p-boxes can overcome these limitations through using all the information available (even if partial) without making over-simplified assumptions. Figure 6.4 shows how imperfect information may be presented in a p-box form on a cumulative distribution function (CDF) whereby A's distribution is known, but not its parameters, B's parameters are known, but not its shape, C has a small empirical dataset, and D is known to be a precise distribution.

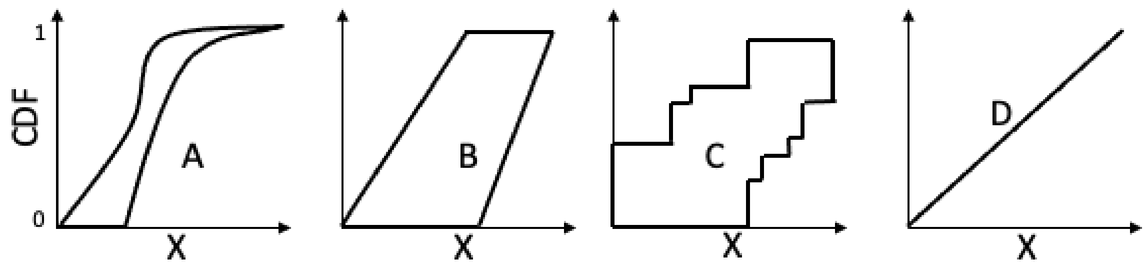

Figure 6.4. Probability boxes representing different types of uncertainty (cf. [399])

The integration of probably bounds analysis enables model inputs with partial information such as an input interval of 30–50 h of direct labour per week (expressed as an min-max interval '30,50'). Moreover, the probability of a pest outbreak occurrence in a given year might be between 35–70% with a single best estimate of 50% (min-max-mean '30,70,50'), with the associated impact being 0–25% of annual yield conveyed as a beta distribution. A breakdown of the risks and their weighting according to model parameters is included within the method statement and found within 'risk_pba.py' within the Model Library in Supplementary Materials. The central limit theorem may be incorporated to give a yield estimate using a normal distribution rather than a precise value [192]. This approach accounts for risks and opportunities that would be nonsensical to provide a precise probability or impact without any historical or peer-reviewed data. In this analysis, the 'pba' package on Python [400,401] was extended to execute the probability bounds analysis necessary.

Once p-boxes are integrated within the model and a simulation has been executed, the resulting finances are analysed. The probability of the cashflows and projected ROI falling below a 'bankruptcy' threshold can be used to predict the event of insolvency defined as the first-hitting-time. First-hitting-time is a method used commonly to predict 'survival' in economics [402,403] and other disciplines [270,404,405]. This hybrid approach of p-boxes with first-passage time has only been applied in one instance for calculating ecological extinction risk [404], and would allow the assessment of financial risk despite deep uncertainty. As historical data and refined inputs are added, the p-box would shrink in size to compute more precise risk-profiling and financial projections.

The quasi-insolvency thresholds are defined as cashflow becoming negative (T_B) and an ROI under a threshold specified by the user (T_{ROI}). Based on a review of bankruptcy models that evaluated whether the most important and frequently used financial ratios are within the profitability group [406], this analysis focuses on the profitability metrics to assess insolvency. The company under analysis is at risk of insolvency when they have no capital runway, which means they will collapse if they do not raise additional capital whilst their revenues and expenses remain unchanged. For ROI, a venture capitalist would typically look for a return of 10–20%+ [77]. The threshold for ROI may vary with time according to investor demands. The probability of insolvency for a given year (INS) is therefore defined in Equation 6.1.

$$P(INS) = P[\,(B < T_B)\ \&\ (ROI < T_{ROI})\,] \tag{6.1}$$

The p-box represents all the possible scenarios modelled and the probabilities of insolvency. The resulting risk analysis can be made useful by introducing categories defined by probability of insolvency over some defined time scale:

- *Critical:* 50% probability of insolvency within 3 years
- *Substantial risk:* 25% probability of insolvency within 5 years
- *Moderate risk:* 10% probability of insolvency within 10 years
- *Safe:* Less than 10% probability of insolvency within 10 years

These categories are mapped onto the analysis to communicate the level of uncertainty and risk profile of the farm. Figure 6.5 shows an example of the risk assessment. The p-box (shaded in grey) primarily falls within the moderate risk category with some creep into safe and critical due to a large degree of uncertainty. This highlights a lack of either precise inputs or information about impacts and the frequency of risks. The future is unknown, but with risk mitigation and corrective action the risk profile could be improved.

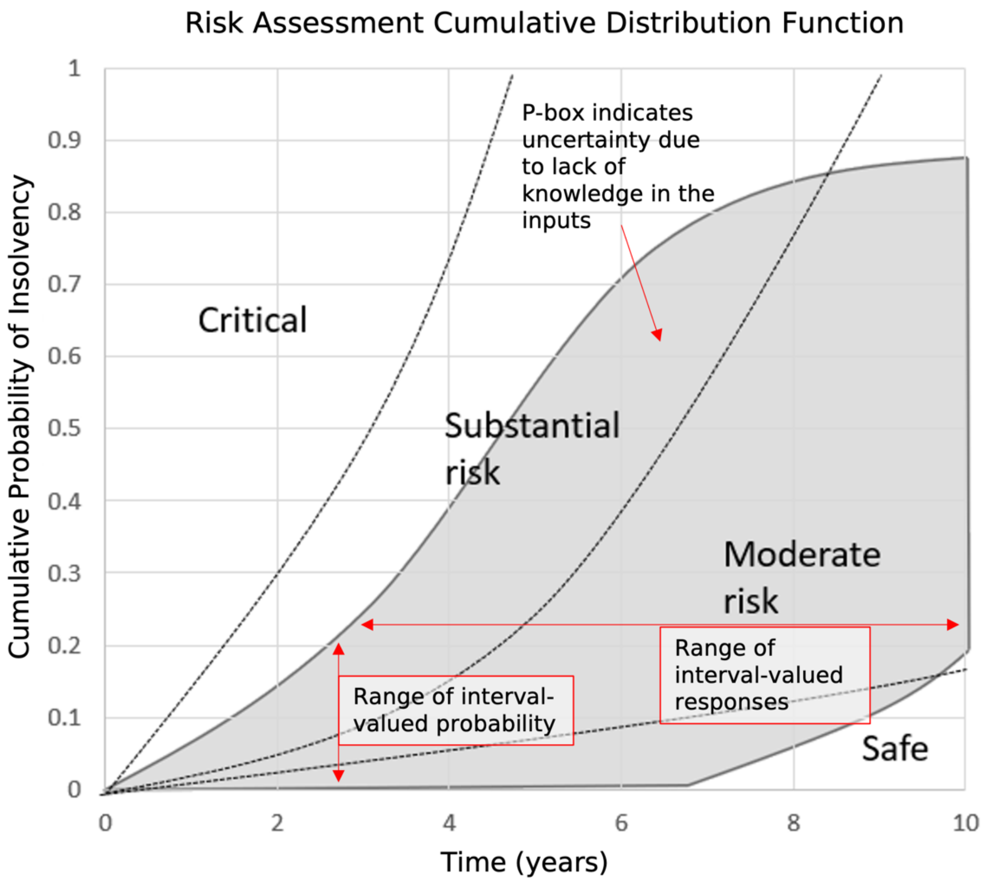

Figure 6.5. A risk curve using probability bounds (shaded in grey) and first-hitting time to evaluate the risk profile of a VF insolvency.

6.4.3 Farm Case Study Inputs and Assumptions

Two vertical farm case studies are used for this analysis: a real commercial vertical farm based in the UK and a hypothetical vertical farm in Japan informed from the literature [63]. The data for the UK case study is for a small-scale commercial VF and has been collected on-site. The information for the Japanese farm is a complete business plan example available within the literature based on the real-world experience of twenty scientists and business managers in the sector [86]. Both examples have been selected because their crop choice of leafy greens is the dominant cultivar in this sector [407]. The methodology described will be applied to both case studies in order to evaluate their profitability and risk profiles. The assumptions about the farm are listed in Table 6.3.

Table 6.3. Assumptions for UK and Japanese case studies (cf. [86]).

UK Vertical Plant Farm	Japanese Vertical Plant Farm
1. The farm has been retro-fitted and installed into a basement rented from a school. The school subsidises rent, electricity and water costs.	1. The farm has been constructed within a leased purpose-built facility.

2. The facility is a pilot with plans to double production capacity in the next year. Therefore, the analysis considers both the pilot and full-scale plan.	2. The facility is at full production capacity with no plan to expand.
3. Vertical towers were modelled as a growing area. The farm's imprecise yield data are used to form upper and lower bounds to compensate for the lack of robust data collection.	3. Nutrient Film Technique (NFT) racks were modelled with the annual yield provided in the example.
4. Lettuce cultivars are grown with twelve plants per tower and a growth cycle of 21 days (after 25 days in the propagation system).	4. Lettuce heads are cultivated in four phases at different spacing: 1st seedling (8 days), 2nd seedling (10 days), transplanting 1st (8 days), transplanting 2nd (8 days).
5. Alternative revenue streams (such as education) are omitted to assess the farm in isolation.	5. No alternative revenue streams are included.
6. Water consumption data are tracked on the farm for 15 months and have been characterised per month: min = 1325 L, max = 8325 L, mean = 3730 L, Standard deviation = 2039 L. Multiplied by 2 for the scaled-up plan.	6. Water costs have been grouped with electricity costs.
7. The facility has a pre-existing HVAC system that has no associated capital costs.	7. A bespoke HVAC system was installed.
8. The indirect team consists of three staff (head grower, marketer, manager).	8. Indirect staff costs were not considered by [86]. This analysis assumes five staff members (CEO, head grower, marketer, engineer and admin).
9. The farm is partly grant-funded for two years.	9. The project is funded with zero interest rates, according to [86].
10. The farm is partially insulated within a thick-brick walled basement but is not sealed, which reduces the climate control capacity.	10. The facility is insulated and benefits from a strictly controlled environment.

A summary of characteristics for the scaled-up UK farm and the hypothetical Japanese are given in Table 6.4. Then, a capital cost breakdown (Table 6.5) is followed by an operational cost breakdown (Table 6.6). All inputs can be found in the Supplementary Data, Table S12 and Table S17. All values are converted to GBP with a conversion rate of 1 USD = 0.72 GBP.

Table 6.4. Farm characteristics summary for UK and Japan farms (adapted with permission from [86]).

Characteristic	UK Farm	Japanese Farm	Unit
Real Estate			
Facility size	220	1000	m^2
Facility height	3	3.5	m
Space utilisation	45	36.4	%
Growing space	100	364	m^2
Systems			
Grow levels	30 towers per rack	6 shelves	
Number. of racks	16	241	
Stacked growing area	392	2184	m^2
Number of lights	256	5784	
Light wattage	100	32	W

Energy price	0.073–0.108	0.090–0.100	£/kWh
Annual electrical consumption	224,255	1,676,052	kWh
Labour			
Number of direct labourers	3	9	people
Number of indirect staff	3	5	people
Direct labour hours per week	20	42	hours per person
Direct hourly cost	9.50	7.34	£/hour
Crop: Lettuce			
Annual yield	8800–10,800	116,640	kg/year
Harvest weight	0.1	0.09	kg
Photoperiod	16	16	hours
Product weight	0.3	1	kg
Customer segmentation	85 (customer 1) 15 (customer 2)	100	% to customers
Unit prices	7.50 (customer 1) 3 (customer 2)	8.64	£/unit
Packaging cost	0.85	0.05	£/unit
Attributes [1]			
Business model	Hybrid	Wholesale	
Grower experience	Medium	High	
Automation level	None	Medium	
Climate control level	Medium	High	
Lighting control level	Medium	High	
Nutrient control level	Medium	High	
CO_2 enrichment	No	Yes	
Biosecurity level	Medium	High	

[1] Definition of input is detailed in method statement in the Supplementary Materials.

Table 6.5. Capital costs breakdown for full-scale UK and Japan farms (adapted with permission from [86]).

Capital costs	UK Farm	Japanese Farm	Unit
Construction			
Finishing	3850	114,775	£
Appliance	4250	108,000	£
Management costs	9029	0	£
Electrical infrastructure	8020	25,200	£
Real estate	0	0	£
Total construction costs	25,149	247,975	£
Systems			
Growing system cost	55,071	747,072	£
Lighting system cost	87,165	538,804	£
HVAC system cost	2700	56,160	£
Miscellaneous cost	9548	0	£
Total equipment cost	154,484	1,342,037	£
Total capital costs	179,633	1,590,012	£

Table 6.6. Operational costs breakdown for the full scale UK and Japan farms (adapted with permission from [86]).

Production Costs	UK Farm	Japanese Farm	Unit

Operational expenditure			
Rent	0	69,120	£/year
Staff costs (non-direct labour)	70,236	171,888 [1]	£/year
Distribution	31,172	106,691	£/year
Other costs [1]	1404–6039	8594 [1]	£/year
Total OpEx	108,998	356,293	£/year
Cost of goods sold			
Direct labour costs	29,640	142,689	£/year
Growing media	5735	14,818	£/year
Packaging	22,977–32,078	2905	£/year
Total electricity cost	15,929–23,416	150,844	£/year
Water cost	97.59	N/A	£/year
Total COGS	104,000	375,192	£/year
Other costs			
Depreciation	20,417	162,454 [1]	£/year
Working capital	251,504	2,160,000	£
Loan amount	158,000	0	£
Loan tenure	7	0	years
Loan interest	5	0	% per year

[1] Inputs have been modelled based on assumptions in absence of data.

6.5 Results

The case study business scenarios (in Section 6.4.3) are simulated over a 15-year period, the typical lifetime of a vertical farm [11], for cash flows and financial risk analysis. They enable the evaluation of economic viability. The graphical results depict the lower bound on the 2.5th percentile (labelled as 'Min'), the upper bound on the 97.5th percentile (`Max'), the lower and upper bounds on the median (labelled as 'Lower Median' and 'Upper Median') of each variable of interest. The median provides insight into the value at which 50% of all the possible scenarios are above or below.

Each case study will include financial balance, annual yield, return on investment and risk assessment. Two of these metrics, financial balance and return on investment, are used to compute the risk of insolvency and therefore include a threshold. In this analysis, the risk is defined as the combination of negative cash flow and underperforming ROI, which is characterised by probability. The cumulative probability of both of these metrics falling under their respective thresholds simultaneously dictates the risk visualised. The model can easily be generalised for other financial metrics or definitions of risk. Other financial metrics and their respective max–min cases considering with and without risks and opportunities are presented in the Supplementary Data in Section B.1 (UK farm) and B.2 (Japanese PFAL). The full results can also be found as 'results_UK.py', 'results_UK_post.xlsx' and ‘results_JPFA.xlsx’ for the UK farm, UK farm post-interventions and Japanese farm respectively within the Model Library in Supplementary Materials.

6.5.1 UK Vertical Farm

The UK small-scale farm begins its operations with a financial balance of £180,000, which is projected over the 15-year period (see Figure 6.6) with increasing uncertainty. 50% of the scenarios represented by the median are split above and below the risk threshold.

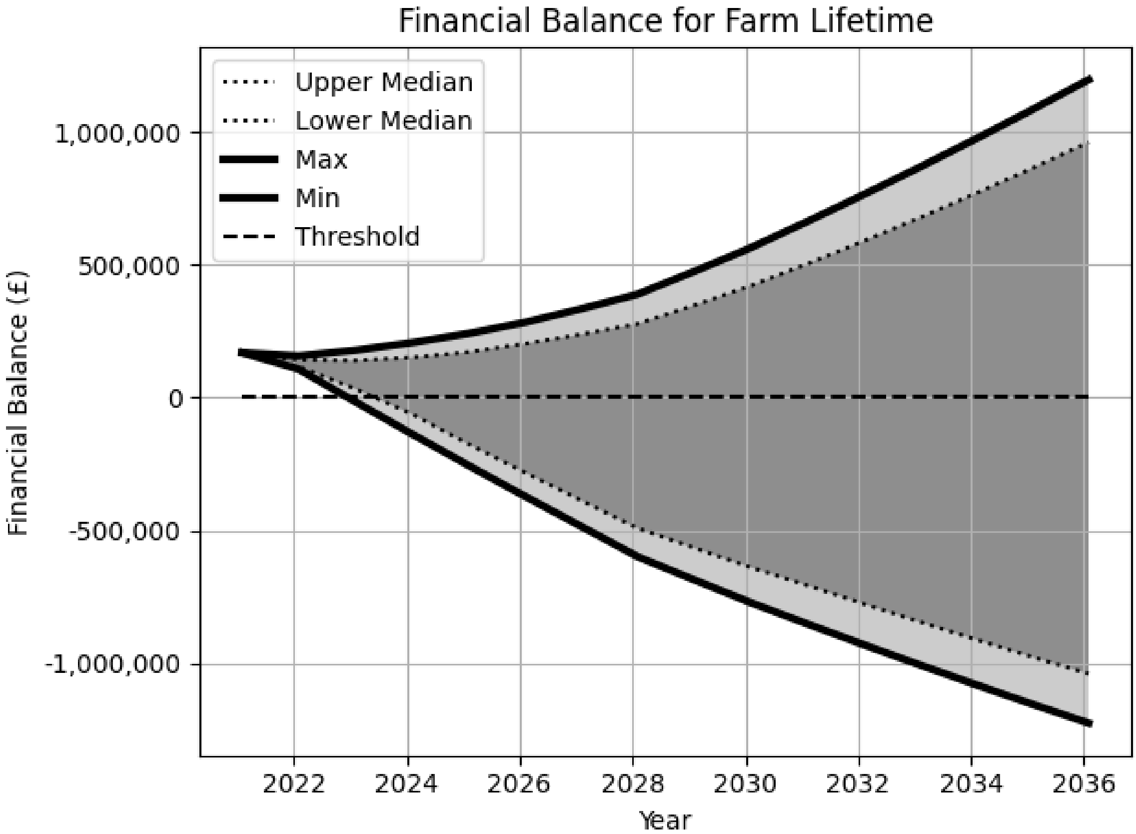

Figure 6.6. Uncertainty about financial balance for the UK farm over the 15-year simulation.

The annual yield for the UK farm for lettuce production is shown in Figure 6.7. There is a sudden increase in yield as the farm scales to full production (doubling the amount of growing systems in the facility) in 2023. There is also a high degree of uncertainty due to the lack of accurate yield tracking on the farm and the possible effects of pathogens and pests. The median is large due to input uncertainty without statistical data such as light efficiency improvements and electricity price. The effect of reducing waste and improving yield as the farm staff gain experience is reflected in the positively increasing gradient of both the max and min scenarios.

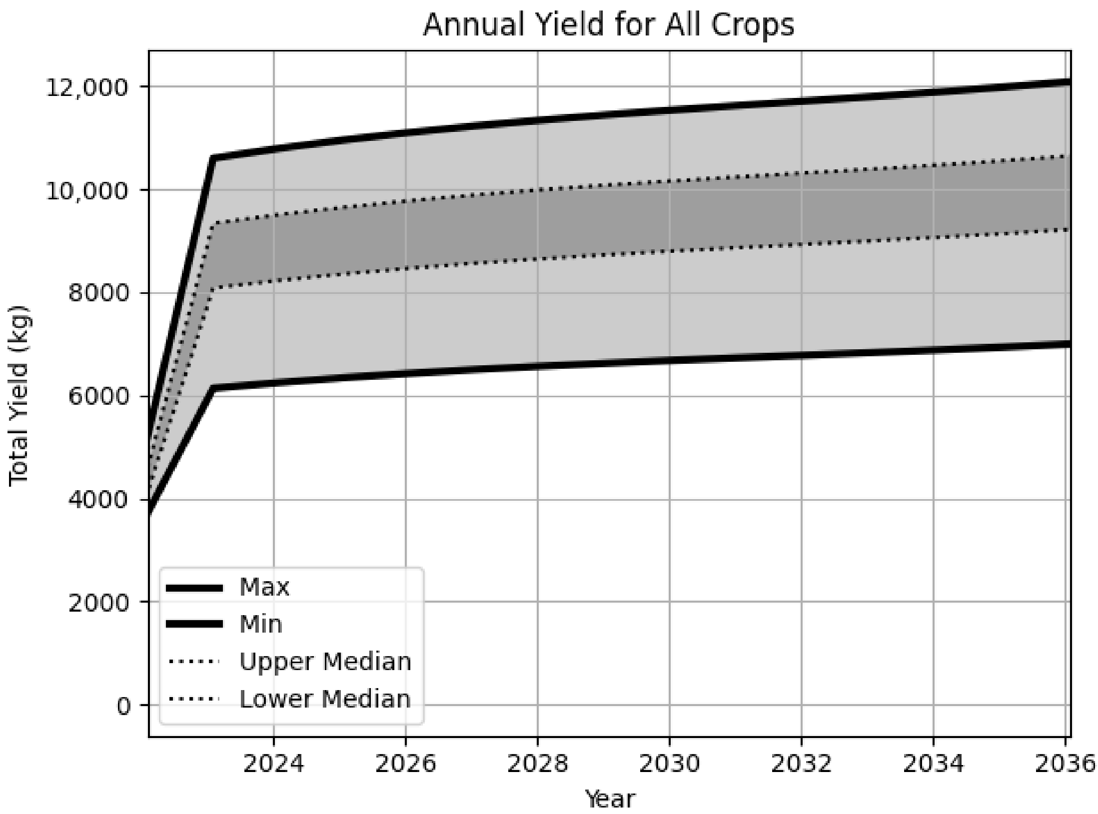

Figure 6.7. The annual yield for the UK farm has a range between 6000 kg and 11,000 kg after scaling up in 2023. The median annual yield would be around 8000 kg, and this will increase with experience.

Figure 6.8 shows the ROI over the farm lifetime. The UK farm has a predicted 15-year cumulative net profit between –£1.50 million and £1.02 million, with an ending ROI of –42% to 61%. The increases are representative of three aspects in chronological order: (i) scaling in production in 2023; (ii) repaying the full loan amount in 2029; and (iii) upgrading to more efficient LED lighting in 2031. Despite these improvements, 50% of the scenarios fall below the required ROI threshold.

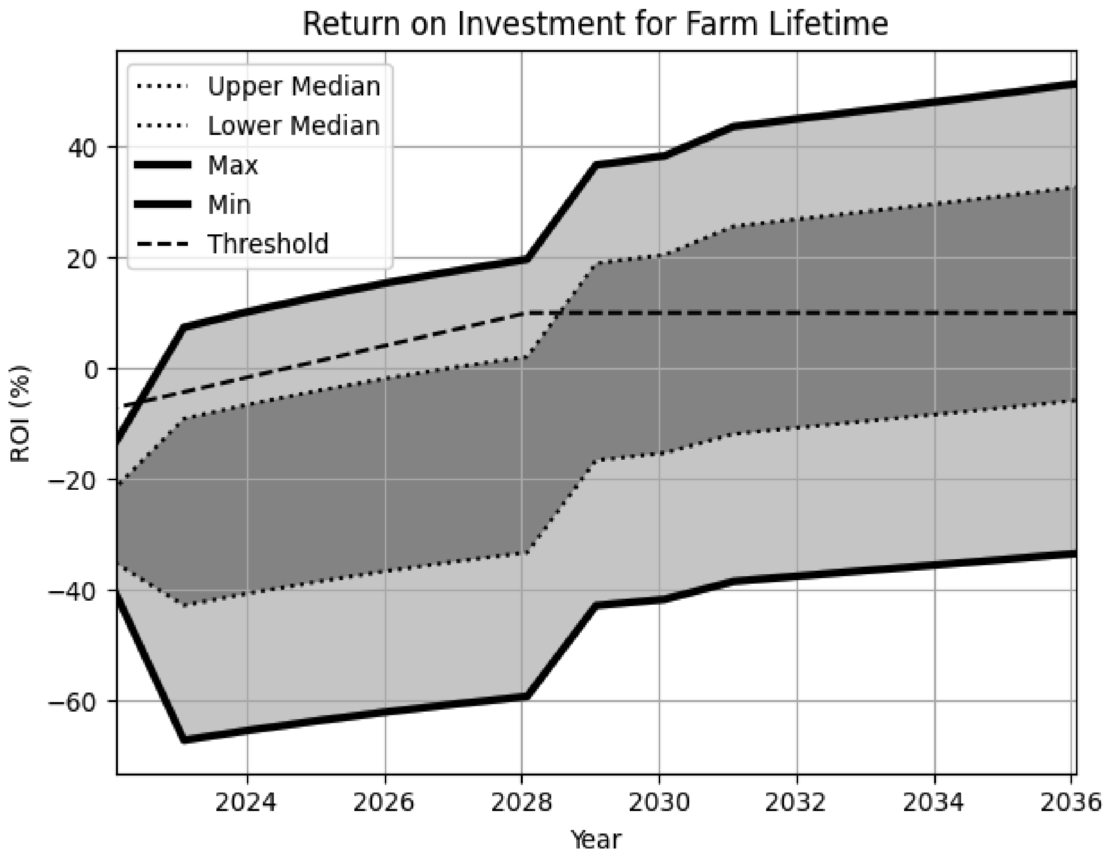

Figure 6.8. ROI potential for UK farm.

The resulting risk assessment for both the financial balance and ROI falling under their respective thresholds is shown in Figure 6.9. It paints an unfavourable picture of the farm, with all considered scenarios between critical and safe after a 2-year timespan indicating large levels of uncertainty and therefore no conclusion can be drawn. This prompts urgent corrective action to fix the business model, improve data collection practices and improve risk mitigation measures to reduce uncertainty. Interventions are discussed in Section 6.6.3.

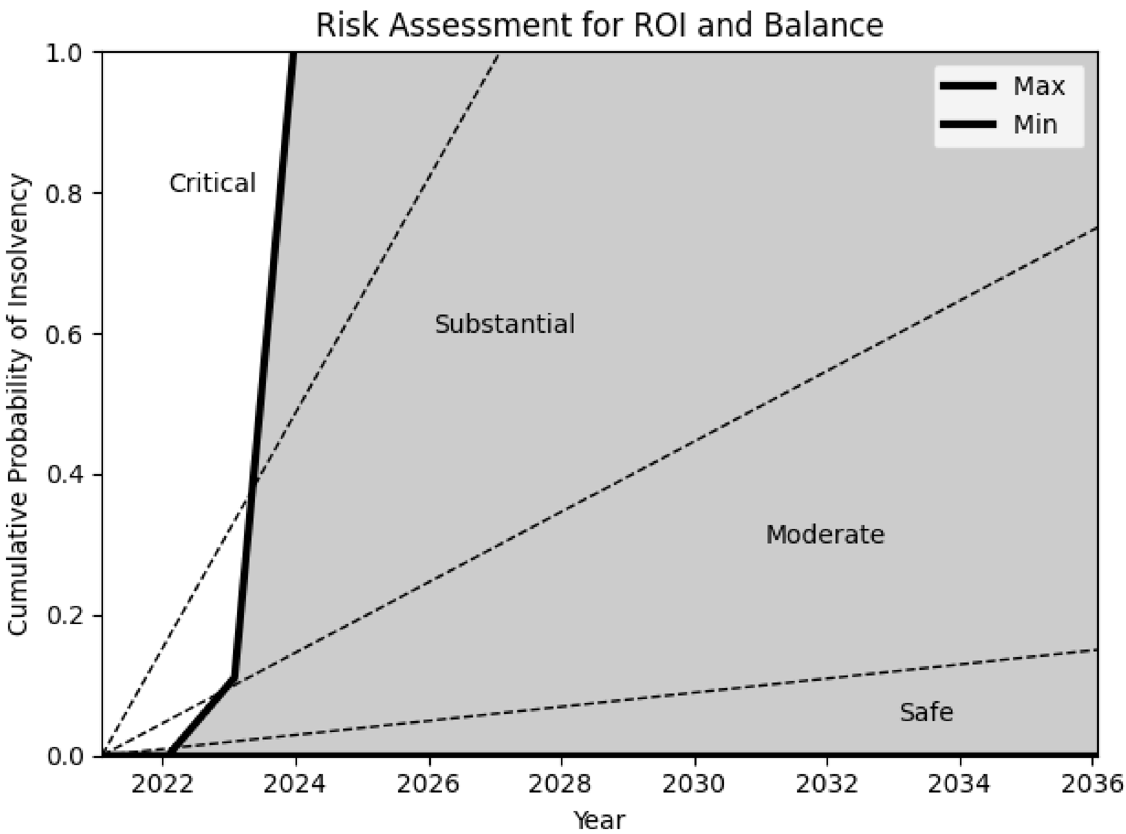

Figure 6.9. Risk profile for financial assessment for the UK farm.

6.5.2 JAPANESE VERTICAL FARM

The Japanese farm begins its operations with a financial balance of almost £570,000 and is projected over a 15-year period (see Figure 6.10). The graph has a narrower median compared to Figure 6.6 because the data provided are more precise. Over 50% of the scenarios, indicated by the dark grey area, are above the financial balance threshold, indicating a profitable business case.

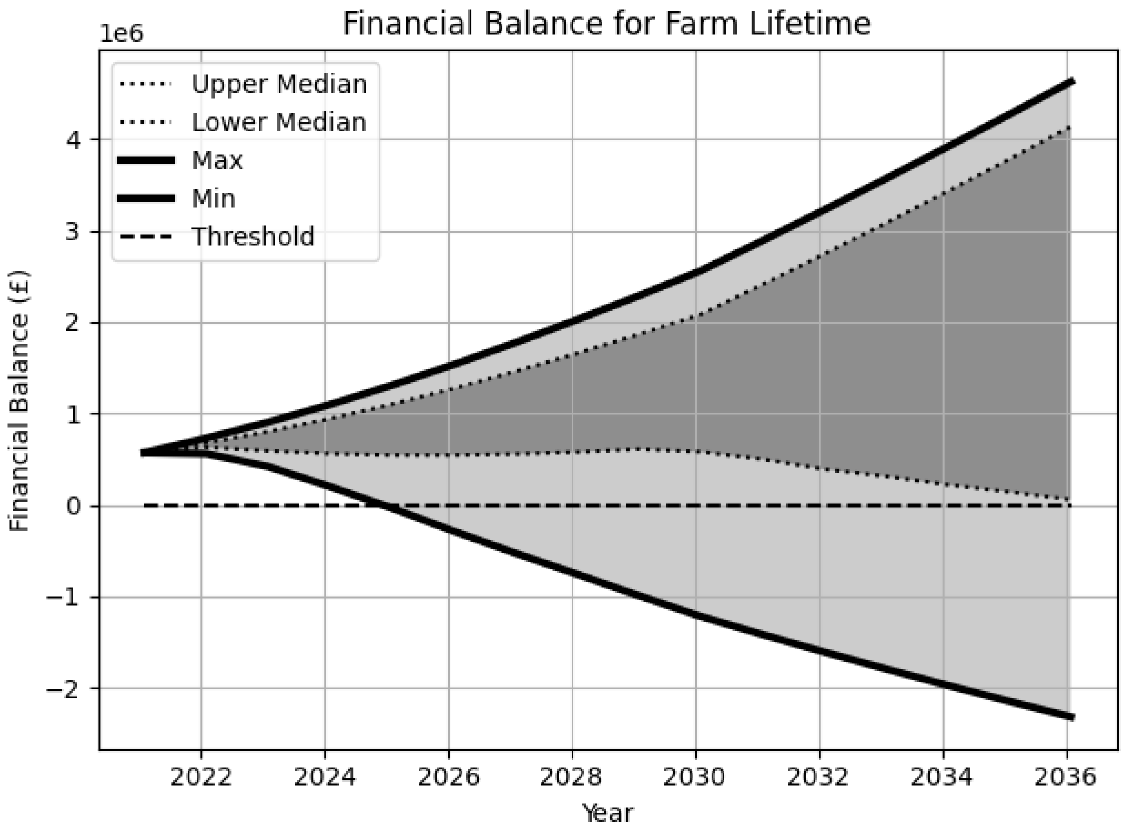

Figure 6.10. Uncertainty about financial balance for the Japanese farm over the 15-year simulation.

The annual yield for the Japanese farm for lettuce is shown in Figure 6.11. There is less uncertainty as the yield tracking is precise compared to the farm in Figure 6.7. The uncertainty remains due to improvements in crop varietals, labour efficiency and growing environment, whilst also having a risk (albeit lower than the UK farm) of pests, pathogens or customer withdrawals.

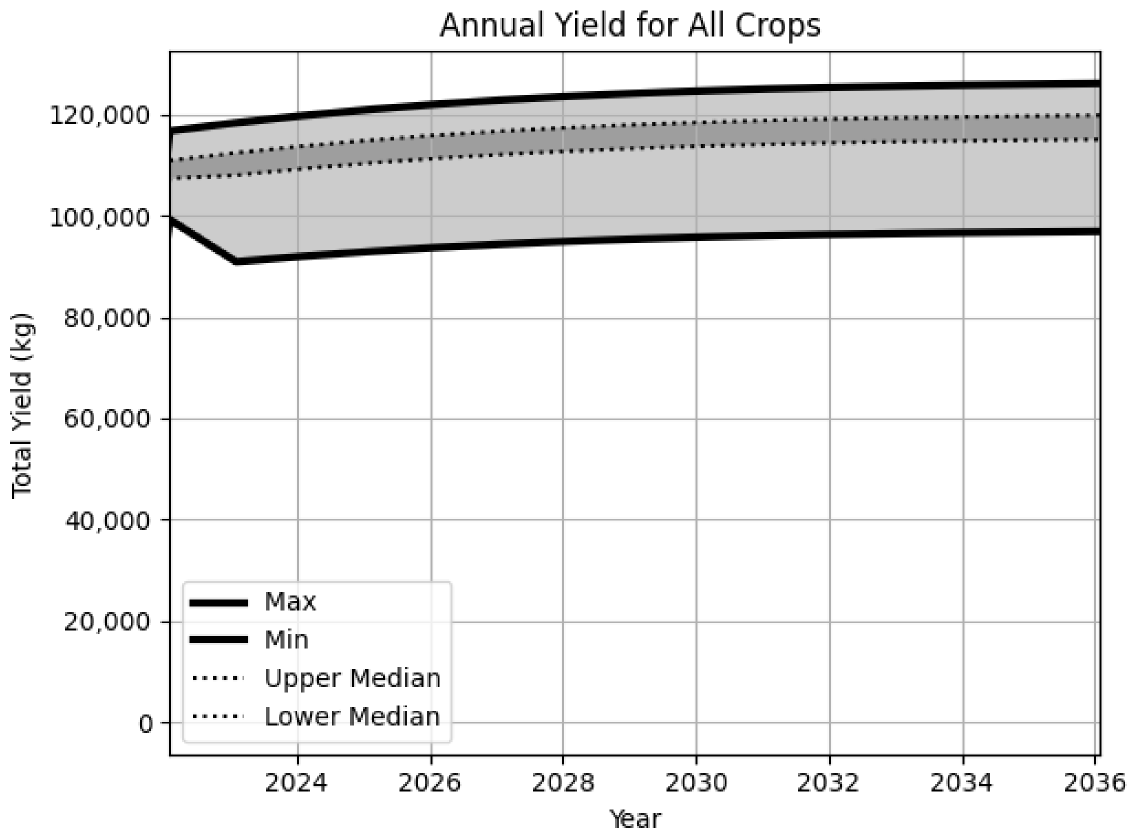

Figure 6.11. Annual yield for Japanese farm has a range between 90,000 kg and 120,000 kg. The median annual yield is 110,000 kg.

The Japanese farm has a predicted 15-year cumulative net profit between –£2.6 million and £4.6 million, with an ending ROI of 0% to 23%. Figure 6.12 shows the ROI over the farm lifetime. Most of the scenarios are profitable and have a positive ROI and after the light efficiency improvement in 2031, over 50% of the scenarios are above the ROI threshold.

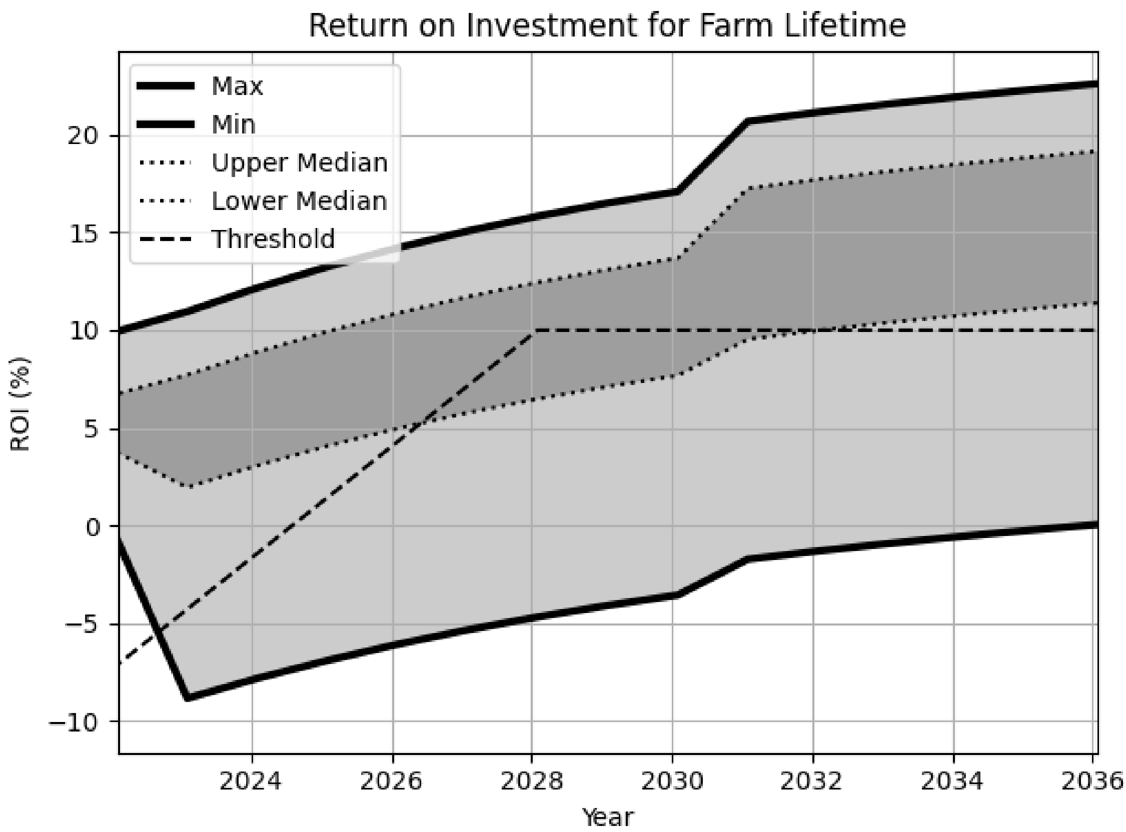

Figure 6.12. ROI potential for Japanese farm.

The resulting risk assessment for the combination of financial balance and ROI falling under their respective thresholds is shown in Figure 6.13. If no risks occur, the farm has 0% probability of insolvency and is in the safe region (best case). If risks such as power outages, equipment failures or crop failure (due to pests or pathogens) occur then the risk of insolvency reaches a 75% cumulative probability by 2029 (substantial risk). The future of the farm therefore lies between substantial and safe risk.

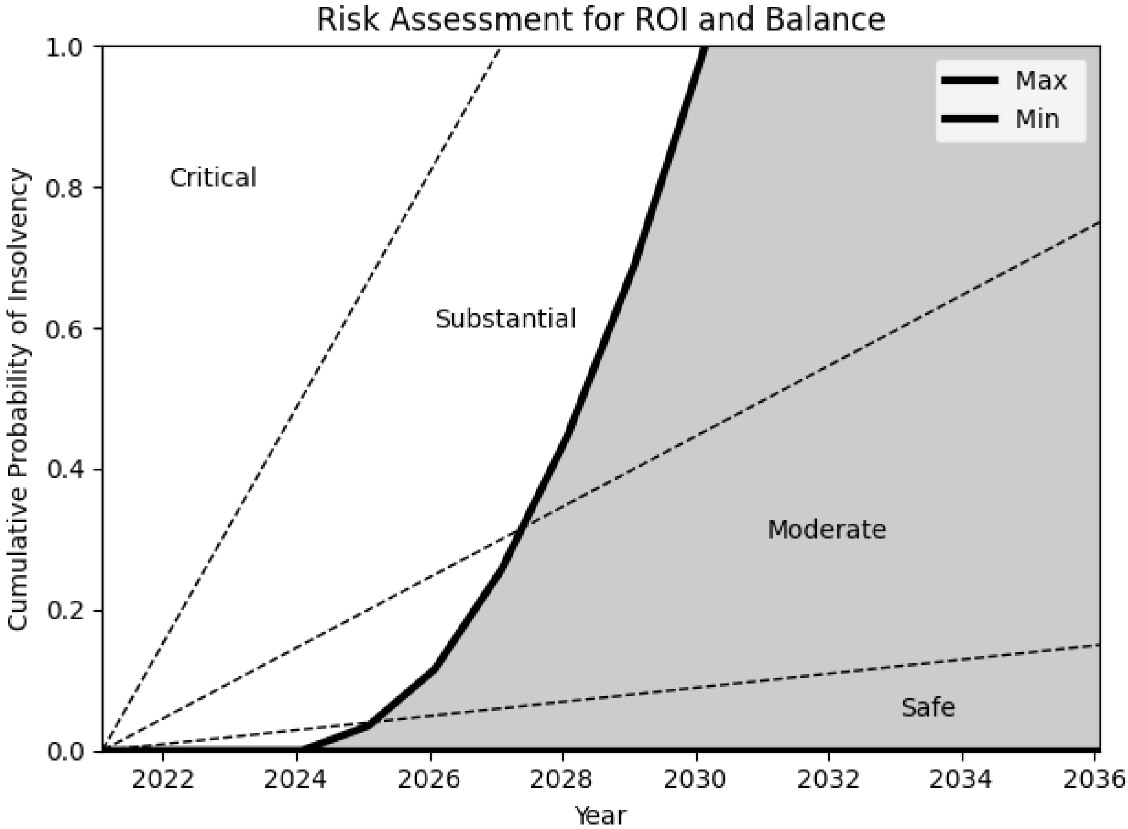

Figure 6.13. The risk profile for the cumulative probability of insolvency over 15 years shows that the Japanese farm has a safe to substantial risk profile.

6.6 DISCUSSION

The model has simplified financial risk assessment by allowing businesses to calculate with both aleatory and epistemic uncertainty without overly precise assumptions using probability bounds. As the VF sector is still in its early stage, entrepreneurs struggle to estimate specific inputs and risks, and this method allows users to sidestep these issues. In this study, a real-life farm (UK) and a hypothetical farm (Japanese) are analysed to evaluate their risk profile in Figure 6.9 and Figure 6.13 according to (6.1). Default risks considered in this analysis are included in Table S4 of the method statement and analysts can create or customise their own risks using 'risk_pba.py' in the Model Library in Supplementary Materials. Users can determine whether the farm is operating at an appropriate scale and with adequate design to make a viable business model. Existing deterministic tools are not sophisticated enough to simultaneously offer best- and worst-case analysis with probability. Applying probability bounds analysis within the context of financial forecasting has never been conducted before within the academic literature. The complexity of indoor VF demands new approaches like this, as many farms have been unable to estimate economics before construction, likely resulting in either unsuccessful fundraising or wasted investments. This section discusses the two case studies, followed by proposed interventions and their effects on the UK case study. The broader implications of using this method are then described, followed by the method's limitations.

6.6.1 UK FARM

Prior expectations for the farm were made based on vertical tower vendor spreadsheets estimating 19,800 kg per year of 'leafy greens' yield extrapolated from the thesis of the vertical farming tower inventor [40,76]. Based on farm data collected for this analysis, an estimated 10,800 kg per year of lettuce will be achieved without intervention, which is 45% less than expected, resulting in drastically reduced profitability prospects. The dilemma for the UK farm is that it is currently operating at a loss and projections for both financial balance and ROI intersect below the thresholds for the majority of the lifetime of the farm. Drastic changes in the business model are required to mitigate this risk. Despite a rent-free location, low-cost labour, and subsidised energy expenditure (up to 50% off the UK average), the potential costs could still outweigh the company's revenues despite the hefty prices that they charge for produce. This indicates that subsidised bills are likely necessary components that should be sought out when developing a viable VF business model. It is worth noting that this analysis has been conducted during the coronavirus pandemic, in which many hospitality businesses are struggling. Customer focus has shifted from a business-to-business model to a business-to-consumer model, and delivering directly to homes has resulted in higher marketing, packaging and delivery costs. This may have led to a costly product and a critical risk profile. The case study was also isolated without considering other revenue streams, such as education-related income, to glean insights into the unit economics of the farm. The lack of hard data, especially for yield, has made evaluating the economics difficult for current farm activities up until now. This analysis enables computation despite unknowns and provides a quantitative evaluation to correct the course towards a financially safer risk profile.

There is a noticeable increase in positive ROI potential due to loan repayments ending and improved lighting efficiency starting in 2028 (Figure 6.8). However, the likelihood of ROI falling below the threshold is substantial, with over 50% of scenarios (shaded in grey) earning insufficient ROI. Further investment is required to be able to keep the farm financially afloat and make necessary changes towards economic sustainability. The model allows experimentation of potential interventions to form a roadmap to profitability. It has achieved this already during validation, as the analysis informed real business changes for the case study farm owners, such as more accurate data collection and adjustment of packaging and distribution methods.

6.6.2 Japanese Farm

Compared to the PFAL referenced [86], this analysis accounts for additional fixed costs like depreciation, staff salaries, and other costs to make it more realistic (see Table 6.6). Therefore, it is expected that the analysis would reveal a reduced ROI (calculated as net profit divided by capital costs) compared to the literature example. In the literature, the PFAL has a 20.5% ROI after five years, whilst this analysis predicts a −5 to 15% ROI after 5 years (50% of the farm scenarios have an ROI between 6–12.5%). The annual yield is the same as the example and is comparably higher per square-metre (117 kg per m^2 per year) than the UK farm (49.1 kg per m^2 per year). This is because the PFAL has been improved for crop varietal, crop growth recipes and labour efficiency.

The Japanese farm has a positive outlook with a risk profile between substantial (worst case) and safe (best case) in Figure 6.13. The unit economics are profitable, and the farm is more resilient to the risks affecting the smaller UK farm (small repairs, pest outbreaks and electrical outages). On the other hand, the Japanese farm may be more prone to labour challenges (due to a larger team size and low-cost workers), costly equipment failures and customer withdrawal (market shocks) from a supermarket for example. The average financial balance and ROI is over the threshold for the most part. However, the size of the P-box is still covering multiple zones indicating uncertainty, primarily driven by the lack of empirical data for the risks and opportunities. The risk profile is more favourable than that for the UK farm and represents an ideal farm in a more mature market. There is still a significant probability of insolvency from 2025 onwards. Changes could be made to the business model such as seeking alternative revenue streams; however, a substantial risk profile is to be expected in an innovative sector. Because the case study is hypothetical, it is not possible to say whether the risk assessment is wholly grounded in reality. Certain aspects, such as the high yield, should be probed further. If desired, the model could be used to trial other decisions and risk mitigation strategies to see how this may reduce financial risk to a safe investment.

6.6.3 Interventions to UK Case Study

The model allows for consideration of alternative decisions to visualise how they alter the farm's business model and risk profile. The UK farm is in a situation of critical risk, and therefore interventions will be focused on this case study. The proposed adjustments could course-correct the farm (defined in Table 6.3) towards more favourable unit economics and a reduction in pathogen and pest risks. Moreover, diversifying revenue streams would reduce reliance on an optimised growing environment that may be difficult to achieve in a retro-fitted structure. Interventions are suggested in Table 6.7 based on learnings from the results in Section 6.5 and through experimentation with model inputs.

Table 6.7. Suggested interventions for UK case study

Intervention	Input Change	Result
Tailor nutrient solution composition to specific lettuce varietal	Nutrient control: medium to high	Improved yield and produce quality by ~10% [1]
Provide carbon dioxide enrichment	CO_2 enrichment: no to yes	Improved yield and produce quality by ~10% [1]
Improve climate control through HVAC system	Climate control: low to medium. Additional 5–20% energy costs	Improved yield by ~5% [1] and reduced likelihood of pathogens and pests[2]
Alter packaging solution with digital information rather than printed leaflets	Reduce cost from £1.00 to £0.70 per unit	Reduced unit costs
Adopt robust biosecurity protocol requiring more regular cleaning of the systems	Biosecurity control: medium to high	Reduced likelihood of pathogen outbreaks [2]
Use efficient distribution channels by focusing on bulk customers	Distribution unit costs are reduced by 50%	Reduced unit costs
Acquire further capital funding for proposed improvements	£100,000 grant in year 2	£20,000–30,000 additional CapEx
Utilise load shifting to optimise electricity prices (see [303])	From £0.073–0.108 to £0.073–0.085	Reduced unit costs
Introduce tours of the farm with a dedicated tour guide	£2000 revenue per month (10% increase/year) and tour guide salary budgeted	Increased revenue and mitigate risk of crop failure severely affecting income
Account for higher expenses associated with CO_2, nutrient solution, biosecurity and tour marketing	From 2% to 5% of salaries	Increased costs

[1] See Equation S6 in method statement, [2] see Tables S2 and S3 of method statement.

The input changes for the model in Table 6.7 are changed within 'main_pba_UK_Farm_interventions.py' which affect the results according to the method statement. The crop limiting factor is still not entirely understood, and crop growth factors like CO_2 factor and nutrient factor effects are estimated according to [76]. The effects of these adjustments can be seen in financial balance and ROI projections (Figure 6.14 and Figure 6.15, respectively). The combination of these two metrics results in financial risk assessment shown in Figure 6.16.

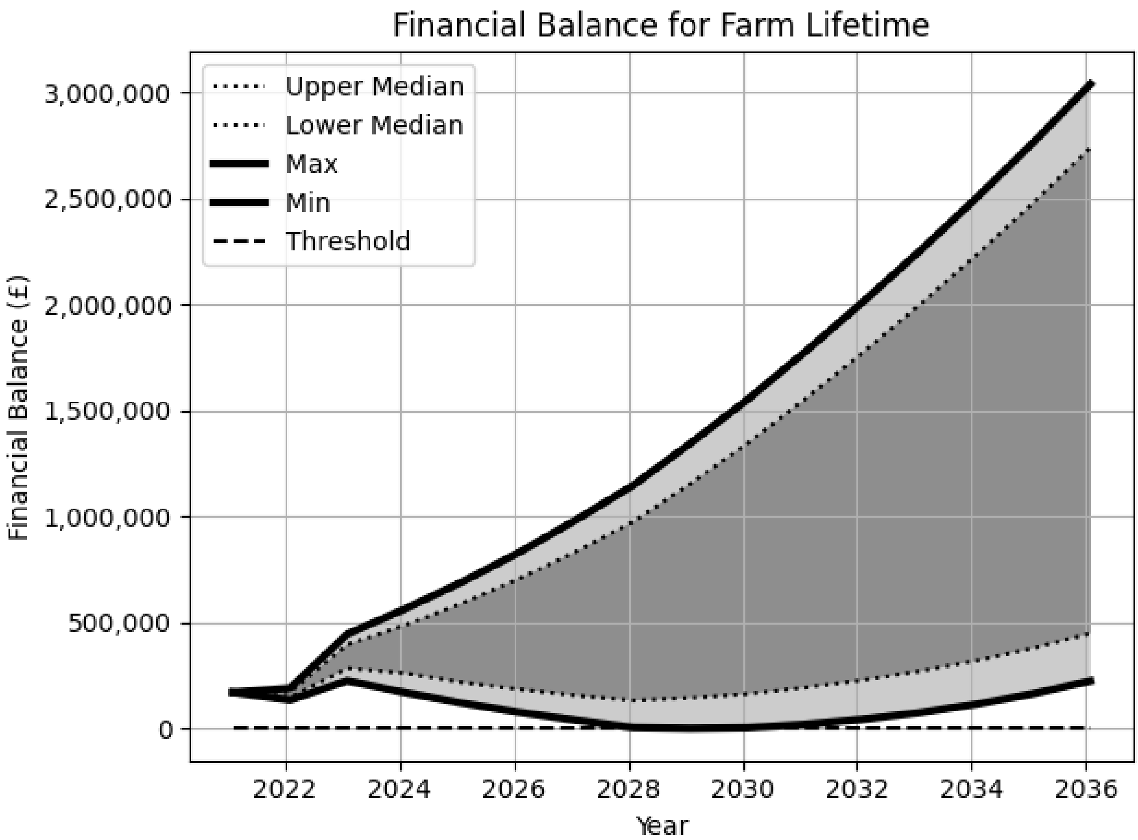

Figure 6.14. Financial balance projections for UK case study after suggested interventions.

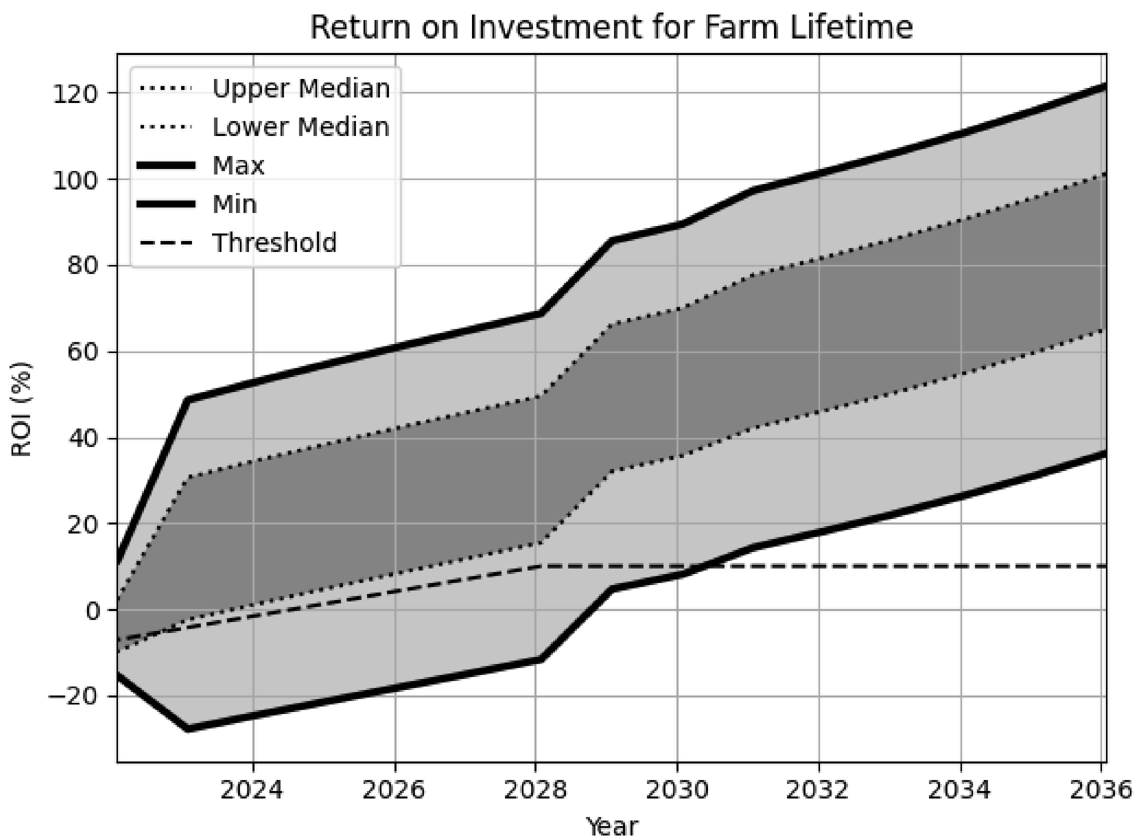

Figure 6.15. ROI projections for UK case study after suggested interventions.

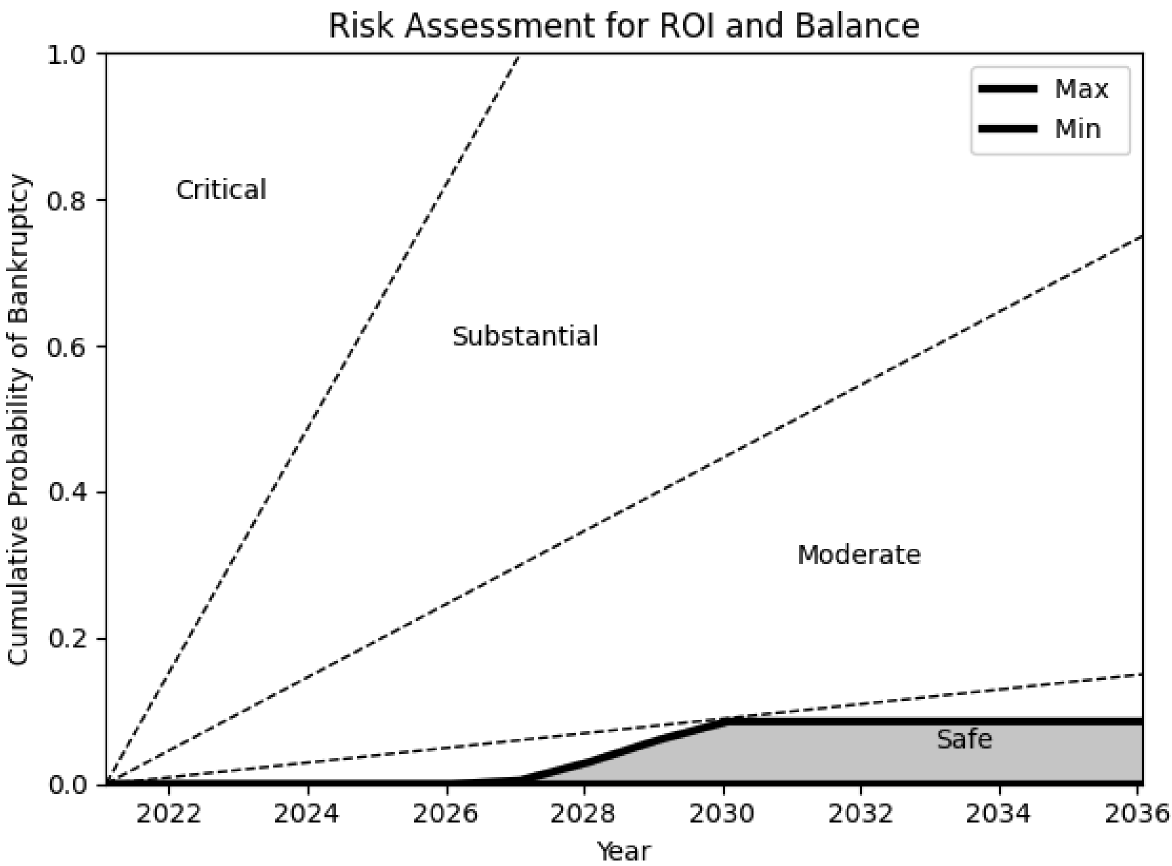

Figure 6.16. Risk profile for the probability of insolvency over 15 years shows that the UK farm is 'safe' after proposed interventions.

The post-intervention risk assessment of Figure 6.16 is now within the safe boundaries for both the worst- and best-case scenarios, providing a vastly more positive and certain outlook than Figure 6.9. There remains epistemic uncertainty that could be reduced through better tracking of yield, direct labour and consumables. This analysis is advantageous for highlighting the urgency in changing trajectory, whilst the company aims to scale up their operations. Further changes could be made, such as selecting higher-value products like speciality herbs; however, market research is required and the scenarios considered show that this is not necessary.

Another consideration is a decentralised model of distribution, whereby systems are placed at distribution points with value-added benefits for a service fee. For example, systems might be placed within a supermarket or within a restaurant and may be replenished from the main farm facility. This is an increasingly popular farm model [150,167,370] and reduces distribution costs. This has been omitted from this analysis and should be integrated in future works. Other revenue streams, such as education, have been riddled with uncertainty and unpredictability due to the coronavirus pandemic but could be included. With the suggested changes in Table 6.7 and without considering risks, the risk profile would improve to a 0% chance of insolvency, indicating a safe investment and a highly profitable model.

6.6.4 IMPLICATIONS

There is a lack of hard financial data publicly available from the VF sector [82], which has led to a debate as to whether or not VF is a profitable endeavour. This model was proposed to directly address this, informing both entrepreneurs and investors to determine the viability of their plans or existing farms. The economic model is the first to enable entrepreneurs within the VF sector to evaluate their business plans whilst considering deep uncertainty. 73% of CEA founders say they would choose their equipment and crop selection differently [293] and through adequate planning this can be reduced. The iterative process of tweaking a business model becomes simplified by allowing users to assess the feasibility of their business decisions without requiring precise assumptions. It helps users understand the components necessary to construct and operate a facility, planning virtually to converge towards a viable business model. Estimating the best and worst cases with an associated probability of survival provides a transparent depiction of companies' futures. Not perfectly knowing the parameters does not preclude a quantitative analysis. Furthermore, the analysis highlights where the uncertainty lies which can help prioritise where more robust data are needed. When partial information about risks and opportunities are known, they can be accounted for selectively to plan for resilience through mitigation strategies. Using risk survey protocols, as utilised in other industries [408], could contribute to further datasets required to enhance analysis. Existing analyses described in Section 6.3 are unable to achieve this. For example, Monte Carlo simulations require more precise assumptions around distributions and therefore can suffer from poor accuracy.

Financial and environmental, social, and governance metrics are also provided as outputs from the model as they become increasingly sought after. Further work is required to examine other case studies across various crop types and configurations to reach conclusions on the most viable business models. This study can have global impacts by enabling entrepreneurs, investors and analysts to assess the production and economics of VF or CEA more widely without overly precise assumptions. Moreover, as probability bounds analysis captures all available information, it is possible to aggregate data of varying quality and across farm types if the uncertainty is correctly accounted for.

6.6.5 LIMITATIONS

There are a few caveats:

- The model evaluates risk assuming the condition of perfect markets (competitive prices exist for all goods in all possible contingencies). Although there exists methods to model imperfect markets [393], these have been omitted from the analysis to avoid excessive uncertainty that reduces the ability to draw any concrete conclusions.
- The model is able to compute yield without the precise user input based on Equation (S6 within the method statement. The relationship between environmental controls and yield is nuanced and this equation adapted from existing research [76] is a simplification of a crop's limiting factor [348]. As this relationship is further understood in the academic literature, this can be expanded to incorporate the limiting factor and provide a more accurate yield estimation.
- Risks and opportunities have been modelled based on anecdotal reports [69]. Meaningful distributions would require longitudinal data of adequate risk reporting (frequency and impacts). A lack of track records means that such data do not currently exist [86]. This is a primary reason for choosing probability bounds analysis, which does not require overly precise estimations. For the time being, risks and opportunities are based on default settings; however, users are welcome to add or modify risks from their own experience and operational history.
- Two case studies have been analysed and juxtaposed to show different systems, markets, climates and scales. Further case studies are required to generate meaningful conclusions about the industry and typical risk profiles. A comparison to a state-of-the-art greenhouse with adjusted risks would give further insight into the risk profile of other production methods. However, this was out of the scope of this article.
- The model has been calibrated to compute realistic financials for both case studies. The analysis would benefit from a more careful validation, requiring longitudinal financial data and operational histories.
- Evaluation of economies of scale would require a deeper analysis of variable costs and how they vary with production quantity across multiple farms.
- The model can compute estimated yields for various crops. However, the analysis presented only examines lettuce farms. Investigating other case studies for other crop types (micro-herbs, mushrooms, berries) may reveal different characteristics, risks and opportunities.

- Other financial indicators such as current ratio, liabilities/total assets ratio, equity/total assets ratio and cash ratio should be included in future iterations of this model.
- Currently the model predicts bankruptcy with the same method regardless of location; however, there is a dependence between explanatory variables and the country, which should be considered in future works [406].

6.7 Conclusions

Industry practitioners claim that the economic viability of vertical farms is possible with a robust business model and a focus on unit economics. However, financial viability requires demonstration and comparative financial data to have scientific validity. A significant obstacle to profitability is knowledge acquisition on how to design and run an efficient VF business. The literature calls for more robust economic analyses for vertical farms. On the other hand, there is a lack of hard data for yields, cost, risks and labour. This study handles partial information by proposing a financial risk model that incorporates the risks and uncertainty of these intricate systems to enhance accuracy.
The method described in this paper assesses economic viability and financial risk despite the lack of available production and financial data. In addition, it can be used to inform improvements in farm design towards profitable business models. The financial risk analysis and model library can be found at: https://github.com/GaiaKnowledge/VerticalFarming (accessed on 16 September 2022) as a part of a wider decision support system project [146]. It utilises probability bounds analysis combined with first-hitting-time, which has been used for other disciplines in ecology and engineering [404]. This method is applied to both real-life (UK) and hypothetical (Japanese) vertical farms.

The UK farm shows that the path to profitability requires many competing factors to be optimised. This aligns with existing research that no specific placement (urban, peri-urban, rural) with varying climate conditions results in a simple net-positive or negative result [407]. For the first time, this can be assessed with incomplete data. The results for the UK case study reveal a critical financial risk (see Figure 6.9) requiring drastic changes to the farm business model. Currently, the farm is operating at a loss, as the business experiments with different technologies, strategies and revenue streams. A path to profitability is being forged through trialing various interventions like further capital injection and improvements to climate control. This collectively results in a more favourable and safe risk profile. The farm operators utilised the model and the results led them to prioritise the collection of more accurate data, especially for metrics that impact profitability.

A real-life case study that shows clear profitability is required in future work to prove or disprove the claim that vertical farms can be profitable. Due to the absence of available data, a Japanese farm from the literature was also used as a hypothetical case study. The hypothetical Japanese farm offers a more resilient business model with an acceptable ROI, but longitudinal data validation is required to determine whether the hypothetical farm is a realistic long-term scenario.

The economic sustainability of vertical farms is primarily driven by high crop yields per unit area as well as electricity, labour and depreciation costs. Despite this, it has become clear from this analysis that using an off-the-shelf system combined with benefits of free rent, low-cost electricity, low-cost labour and a premium price point, does not guarantee positive unit economics and low financial risk. The value that VF delivers to a location is significant and the aforementioned benefits should always be sought out to improve a project's profitability prospects. However, the economics should be carefully evaluated prior to construction. In reality, almost all vertical farms struggle to compare the economic feasibility of different systems and solutions but this can now be achieved more accurately with this economic risk model through allowing analysts to avoid making precise assumptions and more likely to capture true production and financial values.

This analytical research is exploratory and has been conducted on two case studies. It is challenging to draw generalised conclusions on this new industry due to the vast array of business models and proprietary systems being developed. There is no clear formula to profitability and every farm is operating within entirely different constraints (technology, market, climate, building and crop selection). This means that there is no one-size-fits-all approach to VF and each situation should be considered unique. From the model combined with available literature [82,86], it can be deduced that keys to higher profit margins can be found in: (i) scaling operations (whilst fixed costs remain the same); (ii) reducing capital costs due to maturing technology; (iii) improving labour efficiency; (iv) increasing produce quality and yield through crop genetics and growing environment optimization; (v) commanding a premium price; and (vi) reductions in costs such as subsidised rent or electrical efficiency improvement. In future works, more real-life case studies with comprehensive data of various crop types, business models and VF configurations are required to make concrete conclusions about the sector. Longitudinal data of operational histories and financial reporting would enable further validation of the model and facilitate benchmarking that can inform investment decisions. This sector has the potential to radically alter the way we grow and distribute food across the world but only if cost performance can be improved. Risk-empowering businesses, advancing technology, and sharing of data are several aspects that will accelerate this.

As industries become increasingly complex, techniques such as probability bounds analysis already used in other disciplines will be helpful in financial modelling. There is no dispute that the financial futures of start-up businesses are uncertain. Forecasting deterministically or through Monte Carlo simulations provide a simplistic and sometimes inaccurate view. What happens when data about precise model distributions or exact parameters are not available? This is the case for vertical farming. A method such as probability bounds analysis facilitates these computations to open up a new realm of scenario analysis and financial risk management. Vertical farming is only one complex industry of many that could benefit from such a method.

This is the first academic study applying financial risk assessment to vertical farming. By building the foundation of literature on risk in vertical farming, investors can begin to understand this emerging market which will increase access to favourable types of capital. This work enables entrepreneurs, investors, and analysts to assess the production and economics of VF or CEA more widely without overly precise assumptions. Moreover, as probability bounds analysis captures all available information, it is possible to aggregate data of varying quality and across farm types if the uncertainty is correctly accounted for.

6.8 Supplementary Materials

The following are available online at https://www.mdpi.com/article/10.3390/su14095676/s1, Supplementary Data, Method Statement [187,205,268,409–412], Model Library.

6.9 Data Availability Statement

The supporting data are openly available alongside reported results. These can be found in two places, Supplementary Materials (supplementary_data.pdf) and the open-source repository found online at: https://github.com/GaiaKnowledge/VerticalFarming (accessed on 16 September 2022). The UK case study inputs are found as 'Current_Financial_Model_FU_v1.xlsx', processed in 'main_pba_UK_Farm.py' alongside results 'results_UK.xlsx'. The Japanese case study inputs are found as 'Current_Financial_Model_JP_PFAL.xlsx', processed in 'main_pba_JP_PFAL.py' alongside results ‘reuslts_JPFA.xlsx’. The UK farm post interventions is processed as ‘main_pba_UK_Farm_interventions.py’ alongside results ‘results_UK_post.xlsx’. Default data on risks is found at ‘risk_pba.py’.

CHAPTER 7

ENVIRONMENTAL IMPACT MODEL

FRAMING

One of the most significant criticisms of PFALs is the energy consumption and its associated greenhouse gas emissions, with some academics and practitioners refuting that PFALs are sustainable [413]. A prominent industry survey even shows that over 56% of participating CEA businesses (including many indoor vertical farms) think that CEA is prone to excessive "greenwashing", and this increases up to 72% with business experience [148]. The survey also indicates that operators' energy use is the highest priority to improve their sustainability [148]. Finding strategies to reduce associated GHG emissions is of utmost importance as the industry begins to scale [89].

In Chapter 3, an environmental impact model and sustainability metrics were considered crucial elements of the underlying DSS database and model base alongside strategies to reduce the environmental impact of VPF projects. I developed a carbon footprint model for the DSS that enables the user to conduct a full cradle-to-grave life cycle assessment. The model allows the selection of crop type, growing media, annual yield, energy use, energy source, water use, etc. (see Appendix D). For additional comparison, the model allows land-use change across different natural biomes to consider the effects of carbon sequestration in a like-for-like comparison with field-based agriculture. In the absence of data, estimated values are provided that are grounded in data from the literature for energy use, water use and yield per square metre. In this chapter, my colleagues and I validate the model using experimental data from an on-site hydrogen fuel-cell-powered VPF system. Using different energy types, I use the results from their experiment to investigate pathways to net-zero carbon VPF. The study shows the most polluting phases of traditional and VPF practices, which can inform decision support within the DSS. Model assumptions, experimental set-up, experimental results and secondary data are compiled in Appendix D in supplementary Tables S18 to S30.

The study uses the term vertical farming instead of vertical plant farming, as it was written before the completion of Chapter 2. However, the model could be adapted to other crop types.

The article is accepted for publication in *Acta Horticulturae* as "Pathways to net-zero farming: a carbon footprint comparison of vertical versus traditional agriculture". As per their policy, submission of this manuscript implies: that the work described has not been published before (except in the form of a thesis). Therefore this article is contained in this thesis without copyright permission required. In addition, the article underwent a single-blind peer review, and the paper was presented at the International Society for Horticultural Science's International Symposium on Advances in Vertical Farming 2022. The original publication is available at https://actahort.org.

The contributions of the authors are the following: F.B.D.O. conceptualised the project, F.B.D.O designed the project, F.B.D.O programmed the software, F.B.D.O. developed the model, F.B.D.O. validated the software, F.B.D.O. conducted the analysis, L.A., L.E., S.B. conducted the experiment, F.B.D.O. managed the resources, L.E. provided guidance on Hydrogen fuel-cells, F.B.D.O. curated the data, F.B.D.O. wrote the paper, F.B.D.O., J.T., S.B. reviewed and edited the paper, F.B.D.O. visualised the results, and J.T. managed the project. P.M., J.T. supervised, and P.M. acquired funding. All co-authors have agreed to the publication appearing within this PhD thesis.

Sam Bannon, Luke Evans, Laurence Anderson, Paul Myers, and Jens Thomas individually consented to the use of this publication appearing within this thesis.

PATHWAYS TO NET-ZERO FARMING: A CARBON FOOTPRINT COMPARISON OF VERTICAL VERSUS TRADITIONAL AGRICULTURE

Acta Horticulturae

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7.1 ABSTRACT

Agriculture is one of the leading causes of climate change, contributing nearly a quarter of global greenhouse gas emissions. Indoor vertical farming (VF) is a novel form of agriculture offering space savings, water efficiency, and hyper-local production. A significant caveat is the associated CO_2 emissions from energy consumption. We conduct a carbon life-cycle analysis of lettuce production comparing imports from a Spanish field-based farm with hydrogen fuel cell-powered experimental VF in a UK context. We examine the implications of energy source trade-offs and the effects of deforestation. Experimental data using blue hydrogen energy shows emissions for VF as 3.79kg CO_2-eq/kg without and 4.45kg CO_2-eq/kg with the impact of deforestation considered. Associated emissions for field-based imported lettuce are 1.14kg CO_2-eq/kg and 5.05kg CO_2-eq/kg without and with deforestation, respectively. Sensitivity analysis of energy sources in VF shows tidal energy reduces emissions to 1.57kg CO_2-eq/kg with deforestation considered, a third of the emissions from conventional agriculture. Wind, tidal and geothermal energies also show promise for low carbon footprints. The results show that VF with renewable energy sources could provide a lower carbon footprint than imported lettuce from a field-based farm. We believe this is the first attempt to make such a comparison based on real-world data from a VF and consideration of the effects of deforestation.

7.2 INTRODUCTION

Carbon dioxide (CO_2) levels continue to increase within our atmosphere resulting in global warming and volatile weather phenomena. These phenomena have negatively affected agriculture, yet agriculture accounts for 24% of global greenhouse gas emissions [414]. Various challenges face agriculture and international food security requirements, including destructive weather phenomena, water shortages, soil degradation and ageing rural populations [146,415]. Meanwhile, agricultural production must evolve to meet growing food demands whilst adhering to sustainable development goals [416]. Additionally, an estimated 20-70% increase in food production will be necessary to feed 9.7 billion people by 2050 [14]. The global food system has presented the greatest threat to biodiversity [417] through habitat loss and over-exploitation, primarily driven by the demand for food.

One way to improve agricultural productivity is by moving crop production indoors. Controlled environment agriculture (CEA) is a technology-based approach that provides protection and maintains optimal growing conditions. Indoor vertical farming (VF) is a form of CEA that uses hydroponics and vertically stacked systems to increase productivity. VF offers numerous benefits, such as higher water efficiency, better food safety standards, zero pesticide usage, higher yields, increased reliability and lower land footprint [115]. Two caveats to this approach are economics and energy consumption. Most crops are not profitable when grown in this way, and the energy consumption from artificial lighting and temperature control results in significant CO_2 emissions.

Many studies have evaluated the environmental impacts of lettuce production. The majority use Life Cycle Assessment (LCA) methodologies. Most analyses account for resource usage, production outputs and embodied carbon for consumables, equipment and structures [418–420]. Researchers often execute methods with considerable differences (including system boundaries, data inputs, computational methods and results) despite international standards (ISO 14040 and ISO 14044) [421,422]. Especially within the CEA sector, there is a lack of standards for auditing resource consumption and yields [146].

Few analyses evaluate VF, so environmental impact assessment data is limited. [423] reported high CO_2 emissions per unit product for two VF configurations producing lettuce, and Graamans determined that VF requires substantially more energy per unit of production than greenhouses due to using artificial lighting [210]. The limited scope of previous studies is likely due to the difficulties in sourcing data for production and supply chain configurations [420]. Benchmarked data would help overcome these obstacles.

The research on how various renewable energies influence the carbon footprint is scarce. Stoessel et al. suggest that sourcing fruit and vegetables locally is only a good strategy to reduce the carbon footprint if no heating is achieved through fossil fuels

[419]. Uraisami states that clean CO_2-free energy must supply next-generation VF using sources such as off-grid solar power [356]. Deforestation and biodiversity loss are typically omitted from such LCA, as the loss of biodiversity usually occurred long before the analysis. Plants sequester carbon into their biomass [424], and the longer their lifespan, the more carbon is locked up. This is in direct contrast to agricultural land, where crops are harvested, and topsoil is tilled, inhibiting the land's capacity to absorb CO_2. By moving production to VF, agricultural fields could be allowed to return to nature and enable maximum carbon capture, as forest ecosystems are the largest terrestrial carbon sink on Earth [424,425]. One informal analysis points out that considering carbon sequestration of permanent biomass and forests could substantially improve VF's carbon footprints compared to traditional agriculture [425].

This paper compares the CO_2 emissions between field-based and VF lettuce whilst accounting for biodiversity loss through land use and differences in energy sources. Data from a model VF system is used to provide data missing from the existing literature.

7.3 METHODS

An LCA was undertaken to compare the carbon footprint of lettuce production between a traditional field-based model for importing lettuce from the UK's leading exporter (Murcia, Spain) and a vertical farm in the UK. Spain was chosen due to the quantity of lettuce imported to the UK per year during the autumn and winter months, as well as to consider the impact of food miles on the carbon footprint. A cradle-to-grave approach [426] was used and is reflected in the system boundaries (see Figure 7.1). The consumer is considered due to potential differences in customer behaviour and wastage from different supply chains. Indirect aspects such as embedded carbon within the equipment and building structure were omitted in the absence of data. Packaging has been omitted due to the impact being relatively low and because the packaging is likely to be similar regardless of how produce is grown [419].

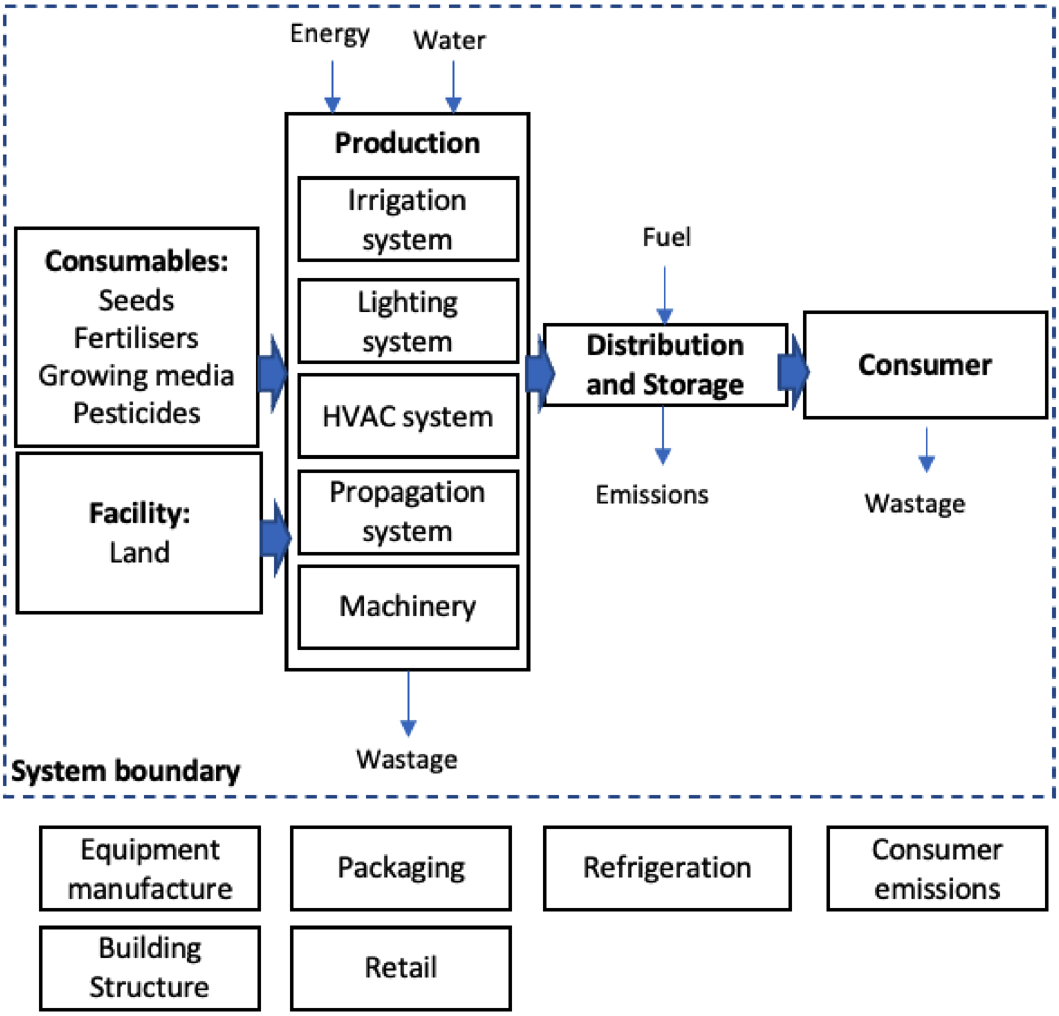

Figure 7.1. Cradle-to-Grave LCA boundaries of the traditional and vertical farms.

The VF case study was conducted at the Heath Business Park in Runcorn, UK. Two small 8-tower, 5-foot vertical tower systems (Zipgrow farm) were used for growing within a 6.6 m^2 facility (50% growing area utilisation. The lettuce cultivar selected was Multi-Leaf Butterhead Salanova Hawking lettuce from Justseed (RZ 79-135) and rockwool plugs were used as the growing media. Data was extrapolated to grow towers converted to 8-foot height. The system was powered by steam methane reforming hydrogen, as supplier TCP-Eco is sited nearby, providing a real-world example of how renewables could be directly incorporated into operations. We assume carbon capture storage in this analysis because of the UK hydrogen strategy to implement 'Blue Hydrogen'.

The functional unit to calculate CO_2 emissions is defined as 1 kg of lettuce sold through a retail supermarket to the end consumer. The resulting carbon footprint is calculated in carbon equivalent units (CO_2-eq) per functional unit. We assume that butterhead lettuce data is a substitute for any cultivar of butterhead lettuce to compare both supply chains [427]. To compare CO_2 emissions for fertiliser use, data from [428] was used, indicating a value for N_{fert} 84 kg ha^{-1} for the application of nitrogen in fertiliser for the field-based growing of lettuce and CO_2 emissions for N-based fertilisers was taken from [429]. Data from a USDA study determined sequestered CO_2 of various biomes [430], and forests were selected as they are the natural biomes for Murcia. Data collection and calculation procedures are according to ISO 14044. The model was implemented within a spreadsheet, available alongside supplementary data at https://github.com/GaiaKnowledge/VerticalFarming.

7.4 Results and Discussion

Table 7.1 lists the model's outputs for annual resource consumption. Comparing the carbon footprint for the conventional farm to the VF whilst excluding deforestation, 1.14 kg of CO_2-eq emissions are associated with 1kg of conventionally grown lettuce. Whilst, 3.79 kg of CO_2-eq is associated with 1 kg of VF lettuce. In this comparison, the emissions associated with conventional farming are a factor of three less than VF. For field-based, the three primary emission sources are food miles (0.521 kg), waste (0.460 kg) and water consumption (0.086 kg). For VF, energy consumption is responsible for the vast majority of the emissions (3.26 kg), with waste (0.573 kg) and nutrients (0.0119 kg) the next largest factors.

Table 7.1. Results for field-based farm and vertical farm from cradle-to-grave alongside associated GHG emissions (Blue Hydrogen for Vertical farm, Spanish grid electricity for conventional)

Phase	**Field-based**		**Vertical farm**	
	Annual amount	kg CO_2-eq per kg of produce	Annual amount	kg CO_2-eq per kg of produce
Yield of lettuce	39,000kg	-	154kg	-
Fertilisers/Nutrients	84kg	0.00310	1.28kg	0.0119
Growing media	0	0	1426 plugs	0.0156
Water consumption	9,750,000 L	0.0860	3079 L	0.00688
Energy consumption	11,920 kWh	0.0510	5802 kWh	0.867-5.65 Mid-range: 3.26
Pesticide usage	5.24kg	0.0104	0 kg	0
Petrol for farm machinery	86.4 L	0.0055	0 L	0
Food miles	2400km	0.5208	25 km	0.0054
Waste	15,600 kg	0.4600	23.09 kg	0.573
Total GHG emissions (excluding deforestation)	44,300kg	1.137	584kg	3.79
Land (deforestation)	10,000 sq-m	3.91	6.6 sq-m	0.653
Total GHG emissions (including deforestation)	197,000kg	5.05	684kg	4.45

The high emissions associated with waste for VF, despite the lower proportion of waste (40% for conventional farming vs. 15% for vertical farming) is due to the CO_2 emissions associated with higher energy consumption. For conventional farming, if the two primary sources (food miles and waste) are excluded, the remaining sources of emissions are an order of magnitude less than these two. Similarly, for VF, if energy consumption and waste are excluded, all other emissions are at least an order of magnitude smaller, and broadly comparable with conventional agriculture. Fertiliser use for VF was 3.8 times higher than for conventional farming, and this brought to light an experimental error that caused 6.2 times more fertiliser to be used in the case study than was required. With this error accounted for, VF would be expected to use 38.6% less fertiliser than conventional farming.

Comparing water use, emissions from conventional farming are an order of magnitude higher than VF and demonstrate VF's value in areas where water consumption is a constraint. Including deforestation in the comparison significantly alters the picture. The emissions for the conventional farm increase to 5.05 kg of CO_2, and that for VF to 4.45 kg of CO_2. In this framing, conventional farming is the source of greater emissions, with VF producing 0.6 kg less CO_2 for each kg of lettuce produced. The size of this change demonstrates the impact that the conversion of wilderness to agricultural land has.

7.4.1 Energy Source Sensitivity Analysis

The above results demonstrate that the electricity used during production is the primary contributor to the carbon footprint for VF. Given that, it is unsurprising that the CO_2 emissions for VF depend heavily on the way the electricity has been generated. Sensitivity analyses were conducted using data from the study of 170 life cycle analyses for different types of power plants [431] to investigate how the total carbon footprint was impacted by changing the source of electricity (Figure 7.2). For comparison, we include the Spanish field-based traditional farm using electricity from the grid, as well as results of a LCA for a USA-based large-scale greenhouse [420].

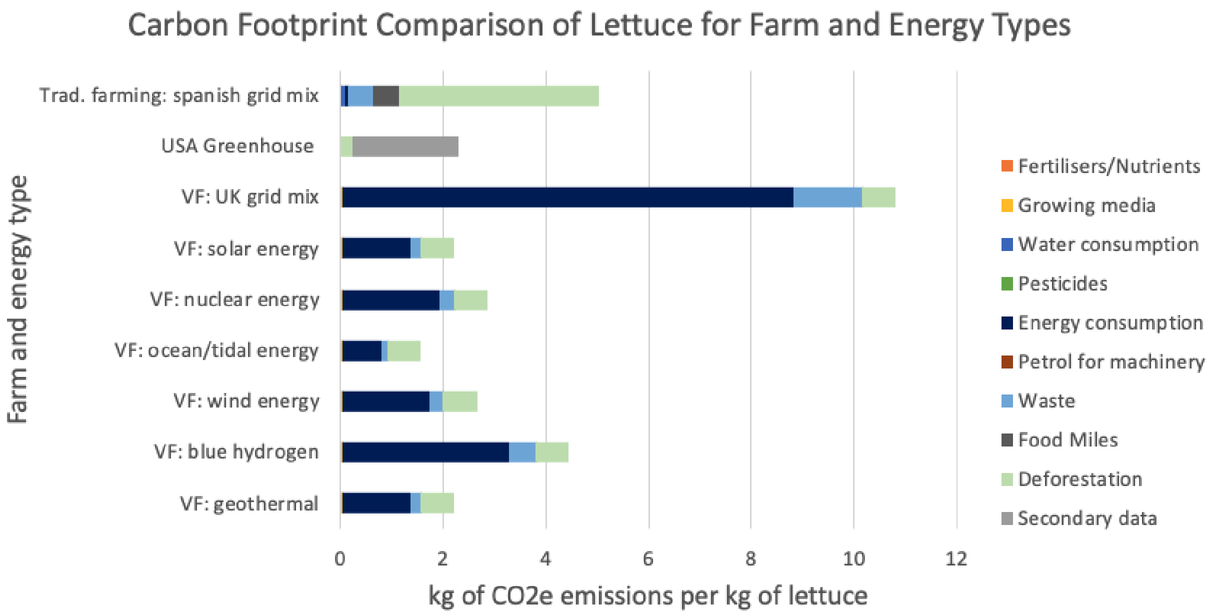

Figure 7.2. CO_2-eq emissions lettuce for field-based, greenhouse, and vertical farms with energy sources.

The analysis shows a wide range, almost a factor of 10, in the impact of energy sources on CO_2 emissions for VF. Sourcing the energy from the current UK Grid, with its mix of primarily non-renewables and some renewables, leads to overall CO_2 emissions of nearly 10.8kg per kg of lettuce (9.67 kg greater than conventional farming). Sourcing the energy from ocean/tidal for VF reduces those emissions to 1.57 kg of CO_2, nearly three times less CO_2 than conventional farming. The greenhouse based in the USA has a relatively low carbon footprint compared with the renewably-powered VF options in Figure 7.2. However, the greenhouse is 6,900 m^2, and the experimental VF set-up is an unoptimised micro-farm. If the VF were a comparable size with an optimised growing environment, the results would likely favour the VF.

As VF transitions to green energy sources, opportunities exist to reduce its carbon footprint to net zero. The potential for VF to integrate circular economy principles in the coming years. VF could co-locate with industrial facilities or office buildings to recycle waste-heat or recapture energy through geothermal solutions. One farm reported recapturing 86% of its energy consumption through geothermal, although this requires validation [69]. Crop breeding for specific indoor varieties may lead to cultivars with less waste. Companies may also choose to offset their remaining emissions by growing trees. Cumulatively, these advancements could show VF's unique potential to be a net-zero form of agriculture.

7.5 Conclusion

This analysis demonstrates the complexities when comparing different food production methods. Many issues affect conventional industrial agriculture, and various efforts are underway to address these, including the targeted application of fertilisers and pesticides, no-till farming methods, and novel crop varieties. These will undoubtedly have a significant impact on emissions. However, reductions will likely only be marginal in the absence of efforts to increase carbon sequestration through farm biodiversity and ecological restoration.

VF offers many benefits, but these come at a cost, overwhelmingly that of energy to power the artificial lighting. Much of this cost can be mitigated if that energy is sourced from renewables. If we further include the high productivity and low area footprint of VF, and the large area of conventional farmland that this productivity liberates, the balance shifts and VF becomes a compelling form of food production that may mitigate carbon emissions. Advancements in VF technology and VF-specific plant breeds whilst integrating circular economy principles may accelerate food production towards net-zero targets.

This is an important discovery. Most analyses of conventional agriculture exclude the effect on the wider environment that turning land into conventional farmland has. However, unless the most beneficial forms of nature-based regenerative agriculture are practised, turning any land into farmland has a significant impact on the surrounding environment.

In a naive comparison with conventional agriculture, it would be easy to portray VF powered by renewable energy as an obvious route to reduce the emissions associated with human food production. This would omit the impact of generating this energy on the environment and its effects on the overall energy demand. Even when considering a farm powered by wind or tidal, these sources' environmental impact and land use requirements need to be factored in to facilitate a more accurate comparison.

CHAPTER 8

DRIVERS OF DECISION SUPPORT SYSTEM ADOPTION IN AGRICULTURE

FRAMING

VPF is typically a high-tech practice using sophisticated systems connected to an internet of things, including sensors, software, machinery, smart devices, and robotics. However, in developing countries, many field-based farmers may not adopt such technologies for reasons such as i) lack of accessibility, ii) lack of technological competence, iii) lack of trust in systems, and iv) high capital cost. DSSs have barely contributed to practical agriculture due to this 'problem of implementation', which has been ascribed to technical limitations of software and farmers' attitudes towards DSSs [245]. I explore these aspects in this chapter by developing a prototype DSS that enables greenhouse farmers in Argentina to keep the required records for good agricultural practices.

This chapter supports the exploration of drivers for technology adoption and DSS usage in agriculture. Although not directly linked to VF, it is connected to the overall project in three ways:

1. The VF DSS proposed in this thesis should integrate lessons from previous agricultural DSSs to increase adoption.
2. The testing of practitioners' responses to decision support may provide transferable insights.
3. Reduction of barriers to technology adoption in developing countries for when VF systems may provide a viable business case in the future.

The contributions of the authors are the following: F.B.D.O. conceptualised the project, F.B.D.O. designed the project, F.B.D.O., A.F. programmed the software, A.F. developed the graphical user interface, F.B.D.O., A.F., M.D.P. validated the software, F.B.D.O. conducted the formal analysis, F.B.D.O., A.F. conducted the investigation, A.F., M.D.P. conducted the interviews, A.F., J.E.H. managed the resources, A.F. curated the data, F.B.D.O. wrote the paper, F.B.D.O., A.F. reviewed and edited the paper, and J.E.H. managed the project.

Alejandro Fernández, Mariana del Pino, and Jorge Hernández individually consented to the use of this publication within this thesis.

DESIGN THINKING AND COMPLIANCE AS DRIVERS FOR DECISION SUPPORT SYSTEM ADOPTION IN AGRICULTURE

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8.1 ABSTRACT

To respond to increasing demands for *good agricultural practices* (GAP) and food safety, governments globally are introducing stringent regulations to govern agricultural compliance that affect production, storage and sales activities. New legislation in Argentina to enforce GAP is an opportunity to test compliance as an incentive to adopt technological solutions. This research aims to determine whether compliance software is an effective gateway to shift farmers' decision-making strategies from intuition-based to evidence-based, improving agricultural productivity through technology. Integrating technology can be a significant hurdle for farms but is also a stepping stone towards more reliable processes. To address this, the authors prototype a decision support system (DSS) for greenhouse farmers in La Plata, Argentina, to help farmers keep traceability records of their crops and treatments to reduce compliance risk. The project incorporates lessons learned from previous DSS projects and utilises design-thinking strategies to involve the end-user in the development.

8.2 INTRODUCTION

Technology and decision support systems (DSSs) have potential to improve food safety, production efficiency and therefore profits for agricultural business especially in developing countries [432]. Their low adoption rates proves a significant hurdle for productivity improvements [245,432,433], however studies suggest that compliance and end-user participation in design could be effective to increase sector-wide use [244,245,433]. This study will explore these drivers further through developing a compliance-focused DSS within a developing economy that is introducing new food safety regulations. The authors introduce the study first through: (i) background of agriculture and technology adoption, (ii) the context of this study conducted in Argentina and (iii) aims and objectives to address the aforementioned challenge.

8.2.1 BACKGROUND

The agriculture landscape is changing. The past five decades have seen a global shift in the field of agriculture from resource-driven growth to productivity-driven growth [432]. Previously, farms have improved agricultural output through the expansion of land, use of pesticides, more fertilisers and other inputs. Now, most farms prioritise the improvement of resource and labour efficiency alongside good agricultural practices (GAP) and technology [432]. Agricultural productivity has been lower in economically developing countries compared to advanced economics, impeding their convergence. Whilst much of the world has embraced technology with open arms, agriculture has adopted it more gradually [432]. Technology and innovation are crucial to accelerate improvements in the sector and embody state-of-the-art practice [432]. The knowledge capital contained within software and hardware can transform farm owners' businesses through improved connection to customers, streamlined supply chains and enhanced yields [432].

DSSs, a type of software solution designed to aid users make better decisions [434], have shown success in both private and public sectors such as healthcare, banking and engineering [435]. They have the potential to benefit farmers by presenting the likelihood of various outcomes from different options [244,434] and can guide users through decision stages by providing expert advice that automatically corresponds to the user's inputs and recorded data for analysis [246]. The analysis conducted by such tools provide data-driven insights which may have otherwise been inaccessible or prone to human error. Despite a wide variety of DSSs for agriculture, studies indicate a disappointingly low uptake [244,245,433] which is amplified in developing countries due to reasons such as technology and software being considered 'risky' by farmers [432]. DSSs have barely contributed to practical agriculture due to this 'problem of implementation' which has been ascribed to technical limitations of software and farmers attitudes towards DSSs [245]. There are numerous detailed analyses on reasons for failure and non-adoption [244,245,433] that will be examined more closely in the related works section.

The adoption of technology in agriculture in developing countries could help provide improvements that do not solely tackle production efficiency but also raise the bar of food quality for higher-value exportable products [432]. This can be a significant growth opportunity for small-holder producers in order to meet the standards of other markets and ultimately catalyse impact on their triple bottom line: social well-being, environmental protection and economic value [436].

Compliance has been identified as an incentive factor for adoption of DSSs in agriculture [244]. Compliance certification schemes, such as global GAP [437], are a method of ameliorating aspects of supply chain traceability and food quality, yet many farms lack the existing systems and processes to reliably track crops from seed to harvest. This includes logging of pesticide treatments that have been approved by local regulatory bodies. Multigenerational farms, and the farms included within this study, can be slow to innovate and they may collect necessary data with pen and paper and transfer this data to spreadsheet tools [438].

declare "the reliability of spreadsheets are essentially the accuracy of the data it produces and is compromised by the errors found in approximately 94% of spreadsheets". These errors are common, non-trivial and can be unforgiving in directly causing catastrophic loss of institutions and companies [439,440]. In the context of Agriculture, data may be incorrectly inputted causing noncompliance and revocation of a contract when perhaps data was inserted correctly but the programme was unable to highlight a breach of compliance enabling swift preventive action.

Through first understanding and then addressing these barriers to technology for farmers, technology developers can improve their confidence using information technology (IT) which is crucial to overcome cultural constraints on technology adoption. Such advancements have the potential to improve labour efficiency, reduce risks and therefore sustain economic growth. Although available software solutions have struggled with low adoption rates [244], many lessons learned from agricultural decision support systems (DSSs) have been identified. One of these is that compliance is an effective means to deliver expert decision support [244]. This is the issue that requires further investigation and that this article aims to explore.

8.2.2 Case Study in La Plata, Argentina

To evaluate whether compliance incentivises technology adoption the authors have designed a study with farmers to take advantage of new regulations. The participants and farmers involved in this study were based in La Plata, Argentina, a horticultural farming region covered with 6000 hectares of greenhouse occupied area with more than 5700 producers [441]. In the last quarter of 2018, the Argentinean government enacted new regulations to govern the application of Food and Agriculture Organisation of the United Nations (FAO)-defined good agricultural practices [442] in the context of vegetable and fruit production [443]. This set of regulations affects the production, storage and sales activities that take place for commercial farms. With regards to chemical applications, the regulation states that farmers are obligated to comply with the recommendations and restrictions of use on the product labels by manufacturers and record any and all applications (under article 2.2.1). Chemicals, soil-additions and fertilisers must be approved for use by SENASA, the National Agri-food Health and Quality Service (see article 2.2.2 for chemicals and 2.6.1 for fertilisers and soil additions) [443]. These changes, that will come into force from January 2020 (for fruits) and January 2021 (for vegetables), represent a unique opportunity to test how a compliance DSS, that addresses the new legislative changes, is able to provide maximum benefit whilst shifting farmers operating protocols to incorporate technology whilst concurrently embedding expert advice and risk mitigation strategies. With this context in mind, this project has been developed as a part of the Risk and Uncertain Conditions for Agriculture Production Systems (RUC-APS) project [444] and working with several horticultural greenhouse farmers in the region of La Plata, Buenos Aires, Argentina.

8.2.3 Aims and Objectives

The authors put forward the hypothesis that a compliance software built with a participative mindset is an effective strategy for the development and adoption of agriculture DSSs and technology solutions. This project aims to integrate lessons learned from previous DSS projects [244,245] to enable the incremental introduction of technology into a farm's processes with continuous end-user feedback and design-thinking strategies. This paper will lay the groundwork for a follow-up study investigating whether an accessible compliance software is an effective gateway for shifting farms decision-making to technology and from intuition-based to evidence-based, improving agricultural productivity. The objectives of this project are as follows:

1. to review the literature and existing software tools for similar functionality, guidelines and reasons for low adoption
2. to select a suitable methodology that includes user-participation within the software development process
3. to develop a DSS prototype, GAP-A-Farm, with farmers in La Plata to address recently introduced compliance regulations and serve as a probe to study adoption
4. to test prototypical features with decision support to examine receptiveness of farmers to expert advice
5. to acquire end-user feedback during the development cycle with farm owners and managers

The paper addresses the objectives in chronological order. *Related Works* presents the approach and the main outcomes of a literature investigation whose goal was to identify the key influencing factors regarding record keeping and decision making in horticulture. The literature investigation also covers existing software tools available on the market and their limitations. *Participative DSS Design* discusses how Design Thinking [445,446] was adopted in this project as a suitable methodology for participatory design. Design-thinking is a methodology for innovation rooted in people centred design and is based on direct observation and user participation as the means to gain a solid understanding of what users want and need. *System Overview* provides an overview of the main features of the resulting DSS system. The system overview discusses inputs such as harvesting, adversity, phytosanitary applications, as well as data about products allowed by local regulation. It also covers outputs detailing how it offers advice to reduce the chance of non-compliance due to the use of unauthorised phytosanitary residues or to the presence of residues in the harvested crops. *Initial Evaluation* presents the results of an initial evaluation based on a survey and a pilot (which is currently underway). Finally, the last section presents the *Conclusions and Future Works*.

8.3 Related Works

The authors conducted an investigation into the literature most relevant to DSSs in agriculture (with particular focus on guidelines and compliance), barriers to their adoption and compliance software tools available to farmers. Firstly, an analysis of literature on DSS was conducted to identify various functions of DSS and reasons for low adoption through searching keywords 'Agriculture Decision Support Tools/Systems', 'Agriculture Apps', Agriculture DSS Low Uptake and 'Review of Agricultural DSS' in Google search engine and Scopus. Secondly, the initial search results yielded thousands of results therefore searches were refined to articles that mentioned barriers to adoption, review of DSS and compliance. Thirdly, a non-exhaustive list of DSS and commercial software tools that address agricultural compliance was collated through searching on iOS/Google app stores and Google search engine for 'farm compliance software/DSS' in both English and Spanish.

Many analyses have been conducted to examine the reasons for DSS low uptake and their failures in agriculture to provide guidelines for future projects [244,245,433,447–449]. Most technological issues associated with DSS use have been significantly reduced due to increased availability of computers, access to the internet and development of web-based DSSs [450]. Two prominent and relevant studies examined previous DSS projects and uncovered reasons for low uptake and concluded key factors for effective design and delivery of such tools [244,245]. They described common issues which align with previous studies, that include:

- failure to consider key aspects of interconnected crop production [245]
- lack of incentives for continued use [244,449]
- poor usability with overwhelming amounts of information [244]
- time intensive due to tedious input requirements and data processing [245,433]
- information is delivered to users at time intervals that are not compatible with decision-making [245]
- DSSs are not regularly maintained and updated [245]
- lack of IT education [244]
- general avoidance of technology [244]

Typically, if the benefit of use outweighs the cost and effort, then there is an incentive, however there are many DSS systems that require inputs that growers struggle to provide with little indication of cost benefits [433]. With the common issues described, the costs of effort can be high (outdated software, investment into learning or unnecessary data collection). Decisions in agriculture are also multidimensional and many programs tend to focus on one specific problem instead of considering how production is interconnected. Also, farmers want to make main decisions, requiring assistance rather than being replaced as a decision-maker [245].

Relevant drivers to adoption that the authors for this study aim to incorporate in their DSS development include: usability, relevance to user and compliance demands [244]. The guidelines proposed within the study by Rose et al. in 2014 [244] suggest that if a developer focuses on time-consuming processes with substantial risk, such as compliance, then it warrants time and effort dedicated from a farmer. From several major reviews on agricultural DSSs, two of which have no mention of DSSs that support compliance [246,451]. One review in 2019, that covered apps for sustainable agriculture, identified software for compliance-related inspection of farms but found that they make no effort to integrate farmer knowledge [451]. Eicher and Dale [451] state the lack of any emphasis on knowledge exchange of evidence-based practices to improve sustainability practices and a disconnect between developers and end-users in early-stages of software development. Another review of farm management information systems in 2015 highlighted that only a few DSSs had features for tracking traceability and providing best practices, however these were in their infancy commercially [452]. Despite this, commercial software solutions have begun to emerge to support record keeping from seed to harvest, in the form of enterprise resource planning (ERP) tools for compliance and these have been discussed in Table 8.1. These tools can be expensive, have limitations such as available languages and can be a leap of faith for traditional farms with potentially technologically illiterate users that require support.

Table 8.1. Software packages available which can be used for agriculture record keeping

Software title	Description	Limitation	Website
Artemis	An application enables growers to optimise facilities and manage people, plants, processes and compliance. Available in multiple languages	Expensive, difficult to implement and data and sensor integration may not be suitable for less technologically minded farms.	https://artemisag.com/
Farmbrite	Web-based software developed by farmers and records seed-to-sale to improve farm management, help with certifications documentation and accounting. Integrates weather forecasts, includes grazing animals interactive maps Able to build online e-Commerce stores	Not available in multiple languages and does not provide local or group decision support based on regulations. Additional features such as E-commerce which may not be necessary.	https://www.farmbrite.com/
SmallHoldr	Global solution tailored for smallholder farms to gain data-driven agronomic advice to achieve higher yields and establish a credit history	No fixed pricing model or free trial. UK-based company with no website translation.	http://www.smallholdr.com/
Microsoft Excel	Spreadsheets are highly customisable and allow for organisation, analysis and storage of data in tabular form. They have been used on farms for decades and are able to handle static data with formulas coded by the user.	Prone to human error with no automation, poor communication of lack of real-time data. No data science integrations and cannot scale.	https://www.microsoft.com/en-gb/microsoft-365/excel

This non-exhaustive review reveals an opportunity to involve end-users in the early development of a compliance based DSS as a vehicle to improve the confidence of farmers in technology solutions. The key takeaways from this review are: (1) that DSSs struggle with low adoption rates, (2) tracking compliance is a time-consuming and laborious process that software tools can make more efficient, (3) compliance and end-user involvement has been listed as a driver towards adoption. There is no research done to date isolating compliance as a driver and testing whether technology addressing record-keeping and regulations can change farmers' attitude towards technology. There is a large opportunity to reduce this pain-point for farms and this is evident by new businesses selling web-based software for record keeping and farm management optimisation. This has become more apparent with the coronavirus pandemic, highlighting ways that technology can aid in farm management with a reduced workforce as well as optimisation in normal circumstances [453] .

8.4 Participative DSS Design

Design thinking, as proposed by Razzouk & Shute [445], is generally defined as "an analytic and creative process that engages a person in opportunities to experiment, create and prototype models, gather feedback, and redesign". The strategy involves a set of processes which can be broken down into initial divergent phases and convergent phases that are iterated. The approach sequentially follows through the five phases: *empathise, define, ideate, prototype and test.* These phases utilise common techniques which are illustrated in Figure 8.1. The goal of the first phase is to gain an empathetic understanding of the user's needs. Through such techniques like interviews, surveys and journey mapping the developers understand some of the core challenges that the farmers encounter regularly. During the definition phase, the designers and stakeholders analyse the information they obtained during the empathise phase, and synthesise the core problems (in the case of our DSS, the core decisions) that need to be supported, enabling clear objectives for the system to emerge. This is followed by sharing of ideas (the ideation phase), thinking of possible solutions and prioritising viable concepts. A minimum viable product (MVP) is created and evaluated by the end-user through mock-ups or storyboards in order to get rapid feedback to validate the software. The MVP mitigates the risk of unnecessary features being developed for the software ensuring its receptibility by the target market. The last step, *test*, allows the developers to find what works and what does not so that unnecessary features can be removed, and the useful features can be improved/added. This approach was iterated over four two-week sprints with several greenhouse farm owners, a senior software developer and a junior developer.

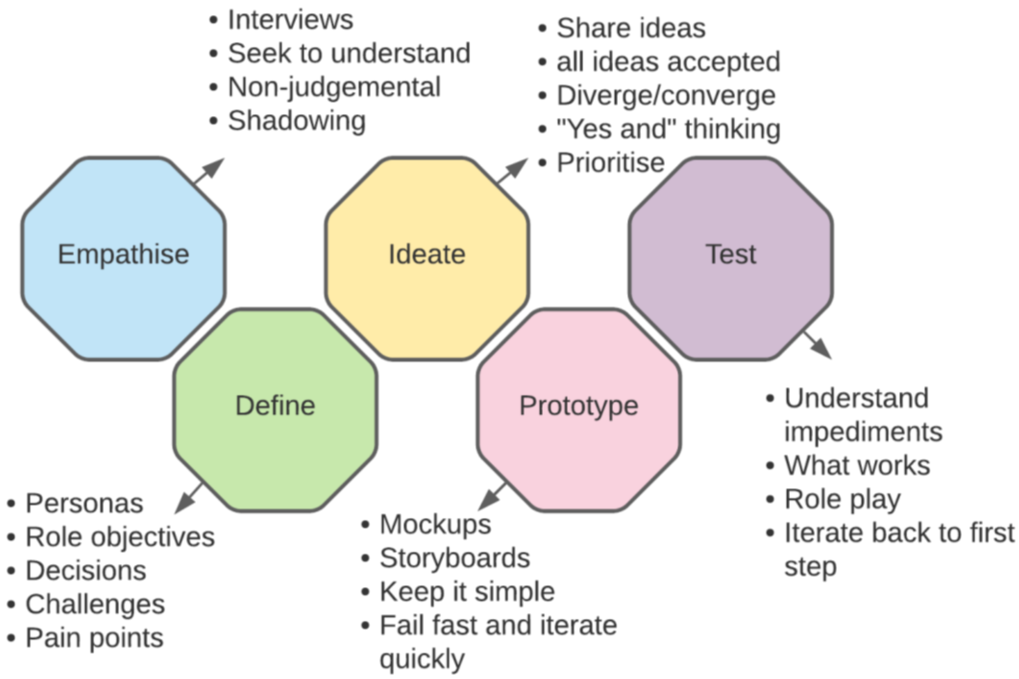

Figure 8.1. Design-thinking phases with actions (adapted from [454] Stanford Design School, 2020)

Following the outlined design-thinking approach, the designers met multiple times with farmers. To complement the interviews and to better identify and define key decisions to support, a short survey with ten participants owning farms between 0.5 to 30 hectares was conducted to identify the key challenges for local indoor farmers, which compliance schemes they follow, their key performance metrics and their existing technological capacity (i.e. number of computers and internet access). The results highlighted that all participants thought technology would be helpful in their processes, however many of them were not sure how they would integrate software and it was clear that they were underprepared to deal with regulatory changes. All the participants agreed that a software would be useful to record traceability and crop planning and they were accustomed to using smartphones to access the internet on their farm, however 70% of those farms did not have access to a desktop computer. 50% of the farms do not track any key performance metrics (indicating intuition-based decisions) and all farms would find comparing their farms to others helpful. The authors concluded that the best solution would be a web-based group DSS to support the necessary compliance processes, provide decision support around authorised substances, premature harvest warning after a chemical application and comparison metrics.

After an examination of how farms think about technology, data and desirable features; additional interviews were conducted with several greenhouse farm businesses that follow existing compliance schemes (primarily Global GAP). These interviews included a series of workshops, the first of which was a journey mapping session to analyse their workflows over harvest cycles and highlight pain points in tracking crops and their treatment plans [455]. The interview sessions enabled a clear definition of the software requirements to adequately record the data for SENASA (the local government organisation) and GAP. The user requirements were agreed to cover the following:

1. Plots can be entered with a history log
2. Plant batches can be sown or harvested within a plots
3. Adversities like pest outbreaks can be reported for batches
4. Treatments like pesticide applications can be reported for batches

Concerns were raised by farmers about whether it would be possible to retrospectively change the logged dates for treatments which indicates that mistakes may be commonly made and records back-dated for compliance. For these reasons, additional features were included such as a warning system to ensure chemical applications are only applied to approved crops by SENASA and crops are not harvested prematurely after a treatment.

After identifying the core functionality of the DSS, an ideation phase followed which resulted in a set of prioritised ideas. Concepts that were discussed through a series of workshops included risk registers, baseline graphs for metrics (yields and pesticide use) utilising group decision support system mechanics, harvest estimation (date and yield) and incorporating a database of SENASA's accepted treatments. The MVP of each of these functions was discussed to see whether they would assist users with decisions they make and determine their benefit. Simple features were then incorporated into a dashboard mock-up and a user journey-map illustrated in Figure 8.2 to get end-user feedback. After accessing the system, farmers are presented with the dashboard. The dashboard offers decision support regarding harvesting dates that are near, trending risks (e.g. pests) in the form of news provided by expert advisors (and based on the reports of multiple farmers), and key performance indicators such as a harvesting progress in relation to plans, and time until the next harvesting starts. From the main screen, farmers can access the details of events in each plot, and can report sowing, adversities (issues), treatments, and harvesting. Information about the products applied during treatment is taken into account to provide decision support previous to harvesting (to avoid harvesting before the mandatory waiting times of the applied products). At all times, farmers can browse and export detailed events records to support the compliance certification processes.

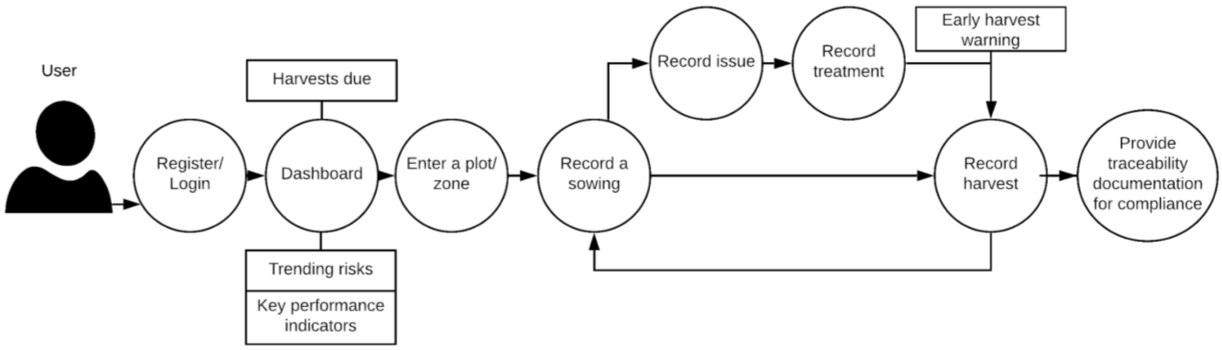

Figure 8.2. User journey (farmer) for MVP developed with the end-users

8.5 SYSTEM OVERVIEW

The prototype tool, GAP-a-Farm, was implemented at the National University of La Plata, and is available under a general public license (GPL) v3.0 on Github (accessible via https://github.com/cientopolis/gap-a-farm) [456]. It foresees two user profiles: experts and farmers. Experts access the system mainly to align the shared catalogue of crops and authorised substances with the information obtained from product labels, and from SENASA. Farmers access the system to record when they plant or discover adversities in the farm (e.g. pests), when they apply chemicals and fertilisers, and when they harvest. This replaces the paper forms or spreadsheets they currently use. Moreover, as farmers use the system, they will discover additional support for decision making, specially focused on GAP compliance. Figure 8.3 provides an overview of the key design abstractions (the data model) that make up GAP-A-Farm. Farms are organised in plots that interact with events and a catalogue of substances and crops aligned to the information provided by the government body, SENASA.

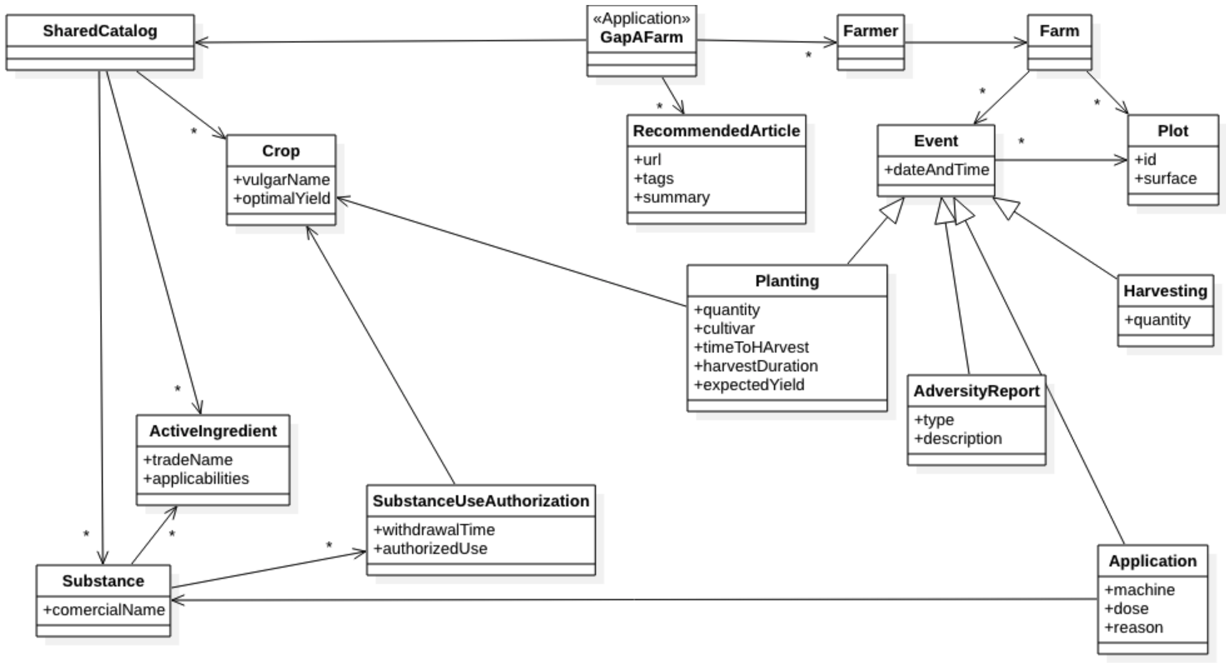

Figure 8.3. Key design abstractions in GAP-A-Farm.

After an initial phase whereby the farmer registers the plots in the farm, most of the interaction of the farmer with the system involves recording relevant events. Events are connected to plots (plots are the minimal unit of analysis). Four types of events are currently available: *Planting*, *Adversity Report*, *Harvesting* and *Application*. In all cases, date and time are recorded.

When planting, the farmer records the crop (choosing one from the shared catalogue) , the quantity (as number of plants or kg of seeds), the time to harvest, the harvest duration, and the expected yield. This information is later turned into dashboard alerts regarding upcoming harvests, to provide targeted news (recommended articles), and to compare expected vs. actual yield.

Upon recording an adversity, the farmer provides a short description (normally the name of a pest) and a classification from a predefined taxonomy (i.e. *Infestation*, *Disease*, *Nutrients Deficiency* or *Other*). Reported adversities are currently used to offer targeted news to farmers and to build a dashboard report of "trending" adversities (that summarises what farmers report). In the future, this would work as a collaborative system providing additional advice as soon as an adversity is reported if farmers share their information.

Recording the application of chemical products and fertilisers is central for compliance. When the farmer records the application of a substance to a plot, the system checks in the shared catalogue that the given substance has been authorised by SENASA for the crop in that plot. Note that the farmer applies the substance under the advice of the farm's agronomist (which can consult the shared catalogue), and it is not up to the system to offer such advice. Moreover, in case SENASA indicated a minimum waiting time before harvesting after application, the system marks the plot as "not to harvest before [date]". This aims to prevent errors in practice rather than requiring the user to change entries retrospectively.

When the harvesting period starts, the farmer records every harvest from every plot. The harvesting event includes information regarding the quantity, both in kilograms, and in a customised unit selected by the farmer (e.g. no. of crates or no. of baskets). Whereas the later was included to reflect common practices, the former is used to update the dashboard report that compared expected to actual (up to date) yield.

As a result of an explicit decision, driven by agility and in pursuit of a MVP, the design has been limited to the data pieces that farmers need to record for compliance certification. The only exception to this rule is the *Planting* event where additional information regarding time to harvest, harvest duration, and expected yield is requested. Although it became clear that farmers do not normally record this information, it was included to assess, during the pilot study, the willingness of farmers to do the extra work if they see how it provides data-driven decision advice.

To ease its deployment and maintenance, the system has been implemented as a web application. This limits its use to farms with internet access, at least. in the management office (which is the case for many farms). It was built using responsive technologies which means that it can be used from both desktop and mobile devices. However, initial discussion with the farmers that will take part in the pilot study suggest that the system will be mainly accessed via desktop computers.

Once the prototype was finished, it was tested with respect to properties such as completeness and internal consistency of the artefacts built; which are a prerequisite to move forward to an evaluation of impact in a follow-up study. GAP-A-Farm went through a series of early testing cycles to ensure alignment to end-users' objectives and usability requirements (efficiency, effectiveness and satisfaction). This meant bringing interactive user-interfaces and mock-ups of additional features to conduct role-play sessions with the end-user. These sessions highlighted challenges in user-flow and additional fields that would be useful (i.e. a notes section for event and customisable units). At the end of the testing phase, a fully functional prototype was available, that included the key functionality for record keeping.

8.6 Initial Evaluation

The goal of the research, to determine whether compliance software is an effective gateway to shift farmers' decision-making strategies from intuition-based to evidence-based, requires a comprehensive and longitudinal evaluation of impact. A longitudinal study has not been conducted as this research is in its preliminary stages, however, initial evaluation was conducted which lays the foundation for future assessment. The primary goal of this initial evaluation is to learn whether widespread adoption of the tool (and sustainable record keeping practices) is possible. This would indicate a first step towards evidence-based decision making. For this initial evaluation, two instruments were combined. Firstly, a demonstration and training session was conducted alongside a survey. Secondly, a pilot was set up as an introduction of the system in real settings. This is currently underway and results are being collected.

8.6.1 Survey

A one-hour online training session was conducted in May 2020. The training session had 39 participants, most of them located Argentina, Chile, Spain and Italy, and with varied backgrounds. The session started with a presentation of the objectives and main features of the system, and a video demonstration followed by a round of questions and answers. Following the training session, participants were invited to participate in a survey aimed at eliciting the participant's opinion with respect to the system. The survey consisted of one multiple selection question, and five short text open questions:

- Which of the following options best describes your function/role/occupation?
- Do you think there is a need/opportunity for tools like GAP-a-Farm?
- Which are the major challenges to take into account if the researchers are to move forward with GAP-a-Farm?
- What do you think are the strengths of GAP-a-Farm?
- What do you think are the weaknesses of GAP-a-Farm?
- If GAP-a-Farm were a cloud service (a web-site where you can record information about your farm), who would be trusted to manage it?

In total, 14 participants completed the survey. Figure 8.4 presents the profile of respondents; they represent the academic, industry and government sector (some participants belong to more than one category).

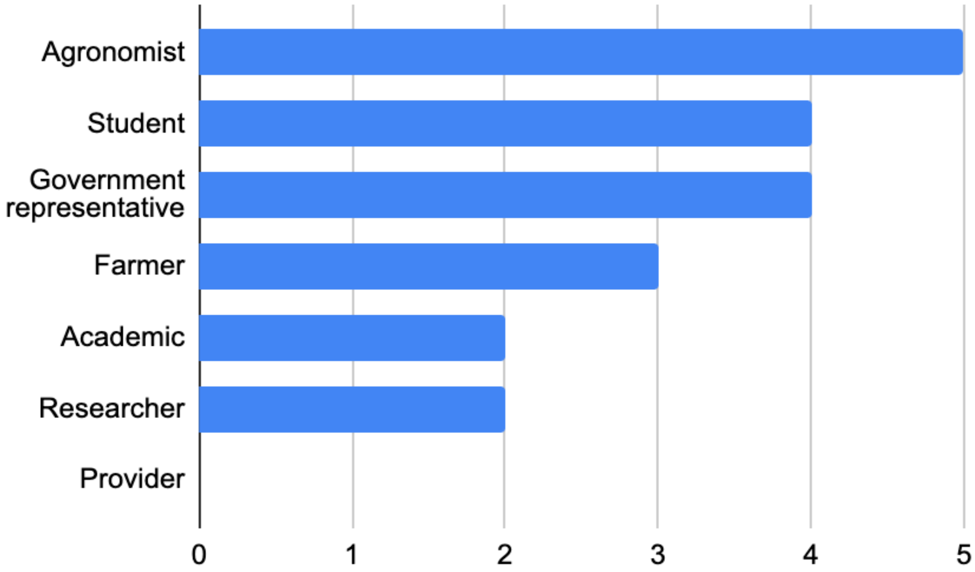

Figure 8.4. Profile of survey respondents

Participants were asked if they considered there was a need/opportunity for a tool like GAP-A-Farm, all respondents answered yes. Respondents identified tool dissemination, adoption, and commitment to use as the main challenges moving forward. Then, the survey asked participants to identify strengths and weaknesses of the tool. The researchers encoded the free text responses (short answers) in the main themes shown in Figure 8.5. Respondents perceived the reduction of the data recording effort, and the ease of use of the tool as two of its strengths. In contrast, they perceived the need to manually record the data as the biggest weakness. These results may appear contradictory at first; however, they can be explained as the recognition of the significant improvement the tool represents when compared to other methods, while still making a claim for further work along this trajectory. Next in order of importance, respondents identified support for the implementation of GAP and for the systemisation of event recording as strengths. The provision of alerts and recommendations, and supporting expert-farmer collaboration were noted as strengths. Still, the lack of usage experience of the tool, and the need for training in GAP and in the usage of the tool are a source of uncertainty about its impact and therefore a weakness. Two responses pointed to missing functionality as a weakness, one of which was related to recording of the use of manure and fertilisers. Although such functionality came up during the design workshops, it was left out of the prototype to limit the scope of the development (that focuses on the application of phytosanitary products affected by government regulation). The other missing functionality report referred generally to "farming machinery" which was interpreted as an interest in the integration of the system with smart machinery, and which requires further analysis.

Strengths	
Effort reduction	8
Perceived ease of use	4
Support of BPAs	4
Systematisation	4
Alerts and recommendations	3
Expert-farmer collaboration	3
Decision support	2

Weaknesses	
Manual data recording	6
Missing usage experience	4
Training and adoption	2
Missing functionality	2

Figure 8.5. Main strengths and weaknesses grouped thematically according to the survey respondents (number of responses on the right)

GAP-A-Farm depends on the centralisation of all recorded data in a single repository. Researchers perceived, in preliminary conversations, that farmers might be reluctant to give other institutions access and control over recorded data. With this in mind, the survey asked participants to indicate which institutions they would entrust their data to. Figure 8.6 summarises their responses. The university represents their first choice, followed by a farmer's organisation and a government agent.

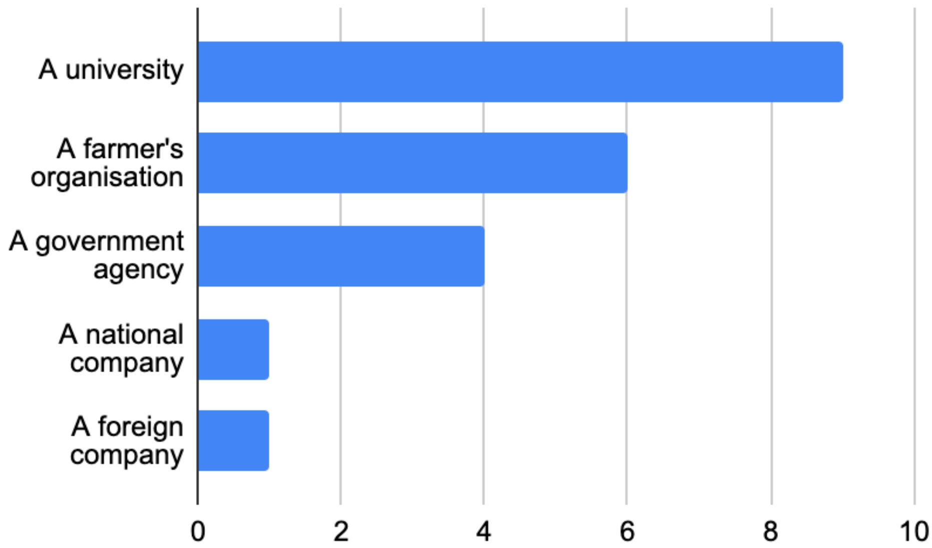

Figure 8.6. Survey results evaluating who farmers would entrust their information to

8.6.2 Pilot study

During the second half of 2020, a pilot study was developed with the objective to collect preliminary data regarding the impact of the use of GAP-a-Farm on the farm's event registry. At the time this article is written, the pilot is underway. Due to the coronavirus pandemic, interaction with participants was limited to what could be conducted on-line. The participants of the pilot include 10 medium horticultural farms from the horticultural green belt of La Plata. Prior to the pilot, representatives of the 10 participating farms were interviewed to discuss their practices and future vision on registration of events and the role of IT. Below, some conclusions obtained from these interviews are summarised.

The first obstacle to event recording is the lack of a map with the layout of the farm, where plots can be identified and georeferenced. Often plots do not have a label/name, so it is impossible to record the events that take place in each one of them. Then, there is also a lack of records of events, and a lack of an orderly management within them. The activities are not explicitly planned, they are executed without being decided and analysed, and therefore they are not evaluated once they are finished in a concrete way. The vast majority of activities are done intuitively and by tradition (almost always the practices are repeated continuously without a justified reason), and this is one of the causes why existing data is not recorded.

The producers of intensive horticulture develop innumerable daily tasks, many of which are not within organisation charts or production planning. Although these tasks are not formally thought or planned, all of them must be executed for the operation of the productive establishment and to fulfil the objective of the establishment, which is to produce the volume of vegetables needed to maintain the economy of the establishment in question. All these activities or events are carried out by the producer or operators, and sometimes occur without keeping a record of them, or keeping records of very few of them.

The sowing dates are useful to know the crop cycles and the yield by season, but for farmers in the pilot it is difficult to take and analyse data. Many times, sowing is performed by operators, who do not record the data anywhere with the subsequent difficulty of its recompiling from memory. When, where and what is sown, typically does not exist as data. If the farmer is not present during the implantation, the farm plants frequently, and grows multiple crops types, registration is even more difficult: these data are lost without being recorded.

To observe and register adversities, one has to know how to identify them and know how to quantify their damage. In this sense, for producers to carry out these records, training is required for this purpose. This is another activity that is done intuitively or by eye. For this reason, applications of phytosanitary products are carried out by frequencies of calendar time (weekly, every ten days, and not under a diagnosis). A few producers have adversity advisers or monitors, and they carry out tighter sanitary programs. Producers who use biological control or who do organic production include monitoring as a diagnostic tool, quantify the damage and use these indicators to make decisions about the application of phytosanitary products.

The harvest of each batch provides potential insights into the yield of the crop, and the incidence of all the variables on the crop in question. The challenge with this registry is that some crops are harvested at staggered times and, in addition crops that come from different lots can overlap, resulting in the confusion of the clear identification of the origin. With quality assurance systems or quality certification systems, the registration of these data is strictly necessary to ensure traceability, a mandatory condition for any type of food certification.

The registration of events is not instilled in the behaviour of the producers, since the horticultural producers do not have training in business, commercial or more professional management. The training of the producers of La Plata is almost entirely based on expert-apprentice experiences within the family. They developed their work history by executing the activities, without programming or analysing them, but rather developing them intuitively, or by family tradition. Producers "know from experience" the result of each activity carried out: soil work, planting the crop, yield, phytosanitary applications, without having evaluated precise data, but rather roughly.

Horticultural production almost always works against the clock with increasing risks, due to climate issues (drought, excess rainfall, soil issues and temperature changes). There are always reasons to work quickly and consequently there is no time to dedicate to recording data. Another problem resides in the fact that, in this type of horticultural establishment, there is not always the data that can be used for decision-making in the different links of the establishment's value chain. Counterproductively they think data is unnecessary, since the activity works under a lot of risk and uncertainty and consider it "waste of time". Therefore, in general, events are not recorded in mixed farms in horticulture because there is no custom, the importance of the data is not believed, it is not known what to use it for and there is no certainty that it will be useful for making decisions. Decisions are often thought to be the correct ones due to their custom, tradition and intuition.

Record keeping was perceived as an important matter, but still secondary in priority to the core activities. The novel coronavirus disease made this gap in relevance even more apparent with urgent action required. Still in this context, most pilot participants confirmed their interest in participation. In one case, the farm hired a person to be in charge of record keeping.

Different strategies for record-keeping will have varying results in terms of efficiency (less effort), effectiveness (fewer errors) and overall satisfaction of the registrant. GAP-A-Farm aims to improve in these aspects, compared to other observed strategies (mainly paper and spreadsheets). Preliminary observations of the loading practices of one of the participants in the pilot project indicate that, when the information to be recorded is available, recording times of each event requires 1 to 2 minutes. In an observed case (an organic producer), 578 events were registered, for which a time investment in the registry of 9 hours is estimated (without considering the data preparation time). For this producer, the records made actually represent less than 15% of what should have been recorded per month. This is a substantial sink of time, especially for producers with many records, because they may have a great variety of crops. The time required to record in GAP-a-Farm and generation of useful data would involve approximately two hours per week of man-hours in labour. However, if the monitoring effort is considered, the time required for the preparation of the data, and the context switching cost (that is, dropping everything else the farmer is doing to sit in front of the computer) the total perceived time for the task is much higher. This could be substantially reduced by utilising mobile app technologies so that there is a distributed way to input into GAP-A-Farm rather than centralised in an office.

8.7 Conclusions and Future Work

The introduction of new agricultural regulation regarding GAP has represented an opportunity to investigate whether compliance software is an effective gateway to shift farmers' decision-making strategies from intuition-based to evidence-based, improving agricultural productivity through technology. Literature confirms that that DSSs struggle with low adoption rates, tracking compliance is a time-consuming and laborious process that software tools can make more efficient, and compliance and end-user involvement have been listed as a driver towards adoption. Design thinking was found to be an effective strategy to involve farmers in the conception of a cloud based, event recording decision support system focused on GAP compliance. Although the study was limited to farmers in La Plata, in Argentina, it already received positive feedback from a wider community through the global RUC-APS (2020) project. The resulting tool, GAP-a-Farm has been released as open source (under GPL3 license and available at: https://github.com/cientopolis/gap-a-farm). A pilot study is now underway involving 10 farms. Early reactions to the pilots evidence two key barriers to methodical record keeping. Firstly, record keeping is perceived as an important but secondary task for farmers; this means they will only conduct it in periods of low farm activity or when record keeping becomes critical (e.g., near the date of a compliance auditing). Secondly, data collection points are scattered and unreliable, consequently increasing the effort and difficulty of the whole event recording process.

One way to balance the scale towards record keeping is to further reduce the effort it represents. Even though farmers recognise that GAP-a-Farm is an improvement, they still indicate data input as a burden. During the pilot, the researchers have observed that certain patterns may exist that would allow form autocompletion, or input prediction. Although at this point it is not clear now much of a time reduction it would imply, these techniques are a clear line for future work. In this regard, techniques such as those proposed by Troiano et al. [457] can be applicable. Additionally, taking a strategic approach to compliance and aligning it with business priorities is an important step to cultural change. One method to do this would be to employ someone whose primary job is to spreadhead the integration of the software and record keeping into the farm processes.

GAP-a-Farm was designed as a web application serving a large community of farmers. This design decision enables collaborative decision support, as data from various farms can be combined and turned into alerts, predictors, advice and baselines for comparisons. Farmers have demonstrated high interest regarding alerts, and moderate interest regarding advice, and baseline comparisons. The pilot has not still reached the point where enough data is available to enable and evaluate such functionality. Future will focus on adjusting collaborative decision support functionality, and learning about the value it delivers to farmers. A longitudinal study is also required to be able to see whether it was a catalyst for further technology integration into farms. The authors expect that such additional value will increase the farmer's motivation to record events.

CHAPTER 9

CONCLUSIONS AND FUTURE WORKS

The research presented in this doctoral dissertation focuses on developing a decision support system (DSS) for vertical plant farming (VPF) operators to address the main barriers to vertical farming VPF scaling and adoption. I approach this from multiple angles: i) classification of farms, ii) DSS development, iii) qualitative analysis of lessons learned, iv) manufacturing principles to improve labour efficiency, v) financial risk assessment, vi) environmental impact assessment, and vii) drivers for decision support system usage. The research and embedded tools aim to help entrepreneurs and investors reduce the high risk of failure they have encountered in developing, funding, and operating vertical plant farms. The work can also be readily adapted to vertical farms of any type. The conclusions from this collection of works are presented here from the perspective of the research questions (RQs) contained in Section 1.1. Following the conclusions, the future works required to upscale the practice of VPF and commercialise the DSS are then described.

9.1 CONCLUSIONS

The seven papers presented in this thesis define the evolution of the research conducted, engaging with the RQs. These RQs are answered by referring to the relevant chapters, with a final statement about the research overall.

- **RQ 1: What technologies, configurations, and business models are being deployed by vertical plant farms?**

There is ambiguity around what vertical farming (VF) is. The definition of vertical farming and a classification taxonomy was required because there is a wide diversity of projects with various crop and animal types and no one-size-fits-all approach. Chapter 2 addresses this need by reviewing VF classifications and identifying VPF configurations and business models. A proposed typology aims to inform operators, policymakers, and investors, about the various VPF projects to expose gaps in knowledge. The industry has been booming and evolved rapidly in the past five years; therefore, Chapter 2 matured throughout the project and was the last piece of research written for the thesis. It reflects the author's present understanding and builds upon some of the latest terminologies to bridge classifications between plant factories with artificial lighting (PFALs), indoor farms, vertical farms, and greenhouses using VF systems. The terms defined in Chapter 2 and the classifications are not reflected throughout the publications within the thesis. However, the background research for Chapter 2 continuously informed the development of the DSS to address the most significant obstacles to vertical farming developments: standardisation, economic viability, and environmental impact.

The terms of open-PFAL, semi-closed-PFAL and closed-PFAL can now encapsulate all indoor vertical plant farms based on the thermal insulation, gas exchange and radiation transmittance levels. The most common configurations for PFALs are farms placed in building interiors using flood and drain, nutrient film technique (NFT), deep flow technique (DFT), or an NFT/DFT hybrid in vertically stacked horizontal systems. Aeroponics and drip irrigation (in standard vertical towers) are increasingly popular. Mobile racking is also being used to increase the space utilisation of the cultivation room. Almost all PFALs use basic automation; however, many are now utilising conveyor automation. Next-generation PFALs have been exploring adaptive automation whereby computers automatically adapt to plants' needs using artificial intelligence without human interference. As far as the authors are aware, this has yet to be fully realised. Over the past five years, the industry has become primarily segmented across three different models: wholesale, retail, and farming-as-a-service. In addition, there are a growing number of farms serving specific niches such as microgreens, animal fodder, plantceuticals, or speciality crops; however, these farms are less publicly visible, and it is challenging to assess their scale. For example, Marijuana is reported to grow well in vertical farming systems, but this area is under-researched in the academic literature.

- **RQ 2: What have been the limitations of economic analyses to date in addressing the economic viability of vertical plant farms?**

No complete and real-life production and financial data were publicly available in the literature, evident by the disparate economic publications that primarily use hypothetical data based on greenhouses. I review these analyses in several chapters; however, the most comprehensive is within Chapter 2 (Section 2.6). The ideal research would examine economics based on real-life case studies. This would provide a credible foundation for literature to build on. Currently, claims that VPF is more profitable than greenhouses require validation due to incomplete datasets. In addition, computing with uncertainty techniques can help develop more accurate cash flow projections to improve accuracy and model uncertain parameters. Uncertainty in data is compounded by rapid technological, economic, and market changes. Risk and uncertainty quantification is seldom used but can bolster such analyses to compensate for the weak datasets for vertically grown plants (most of which use extrapolated greenhouse data) and the lack of benchmarking data. There are a few exceptional and comprehensive analyses assessing the economics and scale of Japanese PFALs, but validated datasets outside of Japan are still needed. None of the analyses considers conveyor automation becoming increasingly popular in the industry.

- **RQ 3: What lessons can be learned from shuttered and operational VPF projects that could support developments?**

In Chapter 4, I conducted a series of industry site visits and interviews with operating and shuttered vertical plant farms (18 participating companies). The data comprised of farms from 3 continents and 8 countries. I used reflexive thematic analysis on the qualitative data from these interviews alongside secondary data sources to examine lessons learned that could inform best practices and identify key failure modes (9 farms had closed). This is the largest existing dataset on shuttered farms. The findings were analysed and disaggregated into 6 themes: economics, labour, growing, technology, strategy, and risk.

The results confirmed that the most significant barriers for VPF were funding and set-up costs. Many farms are spread across multiple R&D and commercial growing objectives, which results in high operating costs and reduced profitability. The appropriate technology selection is critical to positive unit economics, and reverse-engineering the system from the customer and the selected crop is needed to achieve this. Labour challenges also highlight how bottlenecks can severely impact production output, implying how process flow must be considered in the design stages of the farm. Interestingly, profitable farms report that larger growing rooms are not always better for economies of scale. Anecdotally, cultivation rooms of 500 m^2 benefit from better labour efficiency and repairability without introducing contamination risk. However, the study is limited by a relatively small sample size across leafy greens, herbs, microgreens and edible flowers. Further investigation is required amongst larger-scale producers and other crops such as plantceuticals, mushrooms, berries, transplants, fodder, and more.

- **RQ 4: What barriers inhibit vertical farms from scaling and acquiring funding, and how can these be overcome?**

The capital costs to set up a vertical plant farm are disproportionately high relative to other farm types. The CapEx predominantly comprises lighting, growing systems, and building costs (including conversion). Investors and banks are hesitant to fund VPF projects due to the high CapEx, large amount of R&D required, and high risk of failure with knowledge of the risks involved. Operations are also complex, and an incremental scaling approach is more favourable than costly and irreversible decisions. The absence of benchmarking data and proven business models makes the identification of viable farms challenging, if not impossible. The set-up and operating costs will reduce as the technology and market mature; however, entrepreneurs also struggle to forecast their unit economics and development timescales accurately.

Other barriers also prevent the scaling and mainstream adoption of VPF. Firstly, there is a lack of a skilled and trained workforce for the intersection of the technologies required. Customers are also becoming increasingly interested in local and consistent produce without the use of pesticides which PFALs can achieve. In most countries, the current market share of VPF has not reached a critical mass. However, increased consumer awareness and affordability can expand the total addressable market. For example, Japan is home to some of the only profitable PFALs that supply an already food-hygiene-conscious market. Globally, customer adoption could be further catalysed by the continuation of several drivers:

1. Consequences of climate change making field-based agriculture more expensive and challenging.
2. Reductions in the price of VPF produce due to technological and plant science advancements.
3. Disruptions in supply chains from pandemics, geopolitical crises, and rising levels of nationalism.
4. Concerns of food safety due to microbiological, chemical or physical hazards.

In Chapter 3, I proposed a collaborative framework for a DSS to compensate for the significant gaps in knowledge. The framework can estimate economics without precise production or financial data whilst encouraging sharing of benchmarking data, lessons learned, and standardised equipment specifications. In addition, the DSS emphasised risk assessment through a risk register informed by industry interviews and a financial risk methodology to allow entrepreneurs to iterate their business plans and raise additional funding. This article lays out the vision for the DSS and overall PhD project, listing its requirements and uses.

- **RQ 5: What practical improvements can be made for labour efficiency to realise financial viability?**

Chapter 5 examines the highest operating cost and most commonly reported challenge, labour. I aimed to keep this chapter strictly practical, as academic and industry sources describe labour problems; however, there was almost no information on how to improve labour efficiency despite reports from Japanese PFALs that doubling labour productivity is possible. Therefore, I wrote the first publication on integrating manufacturing principles in vertical farming to improve labour efficiency using lean thinking. I worked with an industry partner, Farm Urban, as a case study to implement three lean principles: i) identify value, ii) map the value stream, and iii) create flow. I provide concrete examples of how these methodologies can be incorporated to improve labour efficiencies, such as U-cell layouts, first-in, first-out designs and value stream mapping. Improvements in labour efficiency are estimated in the financial model for the DSS; however, they have not yet been integrated into the decision support provided.

- **RQ 6: How can economic viability be modelled with a lack of available production and financial data?**

Chapter 6 is the cornerstone of this thesis and tackles the most challenging aspect of vertical plant farming, economic viability. Unfortunately, no complete and real-life data sets are publicly available, as discussed earlier. Moreover, there is no academic literature addressing risk in vertical farming other than our publications in Chapters 3 and 4. I executed the approach described in Chapter 3, integrating imprecise probabilities (probability bounds analysis) with a survival (first-hitting-time) financial model to assess financial risk for two case studies: a real-life case-study commercial farm in Liverpool and a hypothetical Japanese plant factory [86]. This is a novel methodology that has not been applied before in the academic literature within a financial risk context, allowing the analyst to forecast in the absence of data. This is especially relevant due to the operational complexity, quick-paced evolution of VF technology, and lack of risk quantification.

The findings of this study revealed that the path to profitability for vertical farms requires many competing factors to be optimised. For example, using an off-the-shelf system to sell premium price produced combined with subsidised rent, electricity, and labour did not automatically guarantee positive unit economics. Therefore, economics should be carefully evaluated prior to construction. In reality, almost all vertical farms struggle to compare the economic feasibility of different systems and solutions, but this can now be achieved more accurately with this financial risk model by allowing analysts to avoid making precise assumptions and be more likely to capture true production and financial values. Imprecise probabilities for financial risk are a relatively overlooked field, with only a couple of examples examining this application [458,459]. As industries become increasingly complex, techniques such as probability bounds analysis already used in other disciplines may be helpful in financial modelling.

- **RQ 7: What are the characteristics of the risks and failure modes that result in the high failure rate of vertical farms?**

There was no research exploring risk in VPF before this work was conducted. This is a significant knowledge gap despite reports that VF is a financially high-risk business. I identified all the reported risks encountered by the farm operators and secondary sources in Chapter 4. However, the farm operators and consultants interviewed could not quantify the likelihood and impact of these risks as intended due to a lack of robust data collection or risk reporting practices within the participating companies. The analysis revealed that vertical farms are weighted more heavily towards labour and technological risks than environmental risks encountered by their field-based counterparts. Tables representing the risks and their occurrence in the interviews are in Section 4.4.6. These can be used to inform project-specific risk registers.

The most common modes of failure were related to funding (70% of closed farms). Farms were either undercapitalised unable to raise further funding, or misaligned between investors' expectations and project goals. The second most reported failure mode was due to labour, or lack thereof. Farm owners struggled to find skilled labour to sustain their operations and could not provide the required time commitment. Another element in failure was building an ambitious project without first conducting a pilot to find a product-market fit. Big projects that have not validated the business model and technology at scale seem to encounter costly obstacles that are difficult to overcome once decisions are locked in place. Some systems were overengineered with more points of failure and, therefore, more repair costs that can bankrupt a farm. According to one consultant, inappropriate technology use was the most frequent cause of failure that they had witnessed. In other cases, they experienced commercial failure with insufficient demand to justify their business case.

The risks are integrated into the 'risk' worksheet in the spreadsheet user interface of the DSS and 'risk.py' of the model. In the financial risk model, default risks can be enabled (switched on/off) to represent pest outbreaks, labour challenges, equipment repairs, customer withdrawals, crop diseases, electrical outages, waste, and construction planning delays (see Appendix B.3). As interviews did not provide sufficient data, risk likelihood and impact were estimated (upper, lower, average, and standard deviation) depending on the degree of closedness, business model, growing experience, and technology used. Opportunities for labour efficiency and electrical efficiency were also modelled. The advantage of using probability bounds analysis to model these risks is that precise probabilities or impacts are not required and allow for the propagation of mixtures between distributions of both aleatory and epistemic uncertainty. The disadvantage is the introduction of more uncertainty. I encourage users of the DSS to either utilise these default risks or insert their own based on their data and experience. A more comprehensive risk register study with data is currently in progress based on site visits conducted at Japanese PFALs.

- **RQ 8: What are the environmental impacts of vertical farms, and how can they be reduced?**

Chapter 7 analyses an experimental vertical farm to conduct a comparative carbon life-cycle assessment between field-based agriculture and vertical farming. I developed and utilised an environmental impact model for the DSS, which was used to analyse the data for this study. Although there have been several examples of life cycle assessment in the literature, I emphasise two aspects that have been previously neglected: space use and its effect on carbon sequestration and the energy type used. The results show that energy consumption, waste, and land-use change, are the primary drivers for greenhouse gas emissions in a vertical farm. Greenhouse gas emissions can be reduced by almost a factor of 10 when comparing the mix of electrical energy from the grid to renewable sources such as ocean energy or geothermal. A field-based farm's greenhouse gas emissions are driven by waste, food miles, and deforestation. Without deforestation considered, a field-based farm's carbon footprint is a fraction of a vertical farm's. However, a vertical farm can be closer to net-zero carbon dioxide emissions with deforestation and renewable energy sources than field-based agriculture.

- **RQ 9: What are the drivers for software adoption in agricultural communities?**

Chapter 8 explores what drives agricultural communities towards technology adoption, particularly for software use such as the DSS described in Chapter 3. I conducted research as a part of a secondment in Argentina with greenhouse growers to explore their barriers to utilising technology that could benefit their production. At the time, there was no commercial use of vertical farms in South America. However, a prerequisite for VPF use by greenhouse and field-based farmers is understanding and trusting technology. VF is more logistically complex with crop cycles throughout the year, which typically require software for data feedback. Several farmers were resistant to the idea of risk management and investing capital towards technology that they did not trust. Some farms experimented with hydroponics but were reluctant to upgrade their nutrient delivery systems because they lacked an understanding of the technology and basic automation. I aimed to identify how a stepping stone can be built towards technology adoption in greenhouses and traditional agriculture, especially in developing economies. The results concluded that design-thinking and compliance are two gateways, and I developed a compliance-based DSS in collaboration with the farmers to deal with new regulations in Argentina. Farmers disliked the cumbersome nature of record-keeping and would like as many fields as possible to be automated. This is likely true for VF operators too, who tend to find the amount of data collected challenging to analyse into actionable insight.

SYNOPSIS

The industry of VPF has several hurdles to overcome to upscale the practice. The project aimed to address the challenges associated with economics, environmental sustainability, and risk management for VPF by providing tools and strategies. A prototype of the DSS was successfully developed to tackle these issues. As a result, the objectives and the research questions have been answered through the chapters presented. How the chapters are integrated and connected to the RQs is visualised in Figure 9.1.

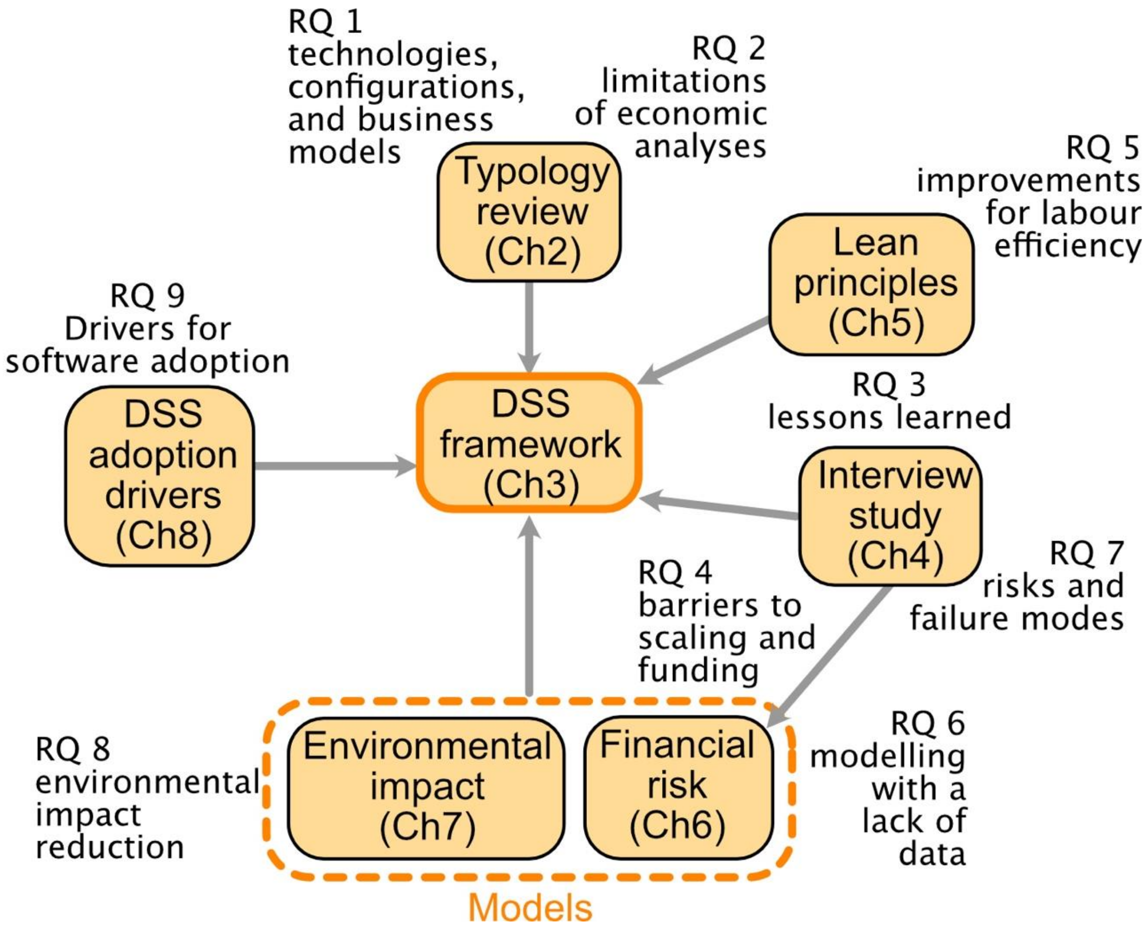

Figure 9.1. The connecting chapters and the corresponding RQs which are answered.

This is the first time risk has been academically explored in VPF, discovering common risks and failure modes. A novel financial risk methodology was developed to compensate for the lack of available data, enabling economic assessment of VPF projects. Strategies for aligning VPF to net-zero carbon targets were also presented, showing how renewable energy types and land-use change may impact the carbon footprint of VPF. These models and tools can be adapted for VF and CEA more broadly.

The financial risk and environmental impact models form the central parts of the DSS framework and can be found at https://github.com/GaiaKnowledge/VerticalFarming (accessed on 24/10/2022).

9.2 Future Works and Recommendations

In this thesis, exploratory research in vertical farming economic and environmental sustainability has been shared, but there is still much work to be done. Nevertheless, the foundation for further research in manufacturing principles, risk assessment, standardisation, and economic viability has been laid.

Currently, the DSS is open-source and retrievable from https://github.com/GaiaKnowledge/VerticalFarming (accessed on 24/10/2022). The DSS is broken down into the economic viability and environmental impact models; however, they are both managed through independent spreadsheets, and risk analysis requires users to configure Python scripts accordingly. Substantial work with software developers and industry-wide cooperation is required to fully commercialise the DSS framework set out in Chapter 3 for a fully functioning graphical user interface that operators can easily use with benchmarked data.

The lessons learned study was an extensive project covering a wide array of topics related to vertical farming. As a result, the risk quantification was diluted, and further work is required with risk reporting protocols over a longitudinal study. This would inform the priors, likelihoods, and impacts used to model the risk assessment accurately. The analysis of risks associated with VPF and the interactions between events, especially in technology and labour, is an area that is still relatively unexplored and open to novel contributions. The author is working on a deeper examination of operational risks experienced by closed-PFALs from fieldwork in Japan.

The interviews also show that many practitioners poorly understand certain aspects that need to be explored, particularly around food safety. Food safety practices, identifying the crop limiting factor, process flow, crop growth recipes, and standardised data are all elements that require further research. Without guidelines for these, many farms engage in duplicative efforts that detract from commercial growing.

Despite practitioners calling for manufacturing principles to be applied to VF and system designs to incorporate such ideas, there is hardly any discussion of practical examples in the literature. Further research in principles of motion economy to improve manual work in vertical farms is sorely needed to improve the quality of life for workers and improve labour efficiency. This plays a decisive role in the profitability of vertical farming operations. From an automation perspective, there is no literature showing the cost-benefit and labour efficiency savings from introducing automated machinery within VF. This is also a fertile area for novel research.

The financial risk model of vertical farming was applied to two case studies. More case studies are required to provide more general conclusions. Furthermore, the model could be substantially improved by integrating market sentiment and climate control. Many default parameters require further validation to improve the precision of the results and reduce uncertainty. Additional risks and their distributions can be incorporated with longitudinal risk data.

The environmental sustainability study shows potential for vertical farms to be more environmentally sustainable when the land use is considered alongside renewable energy and circular economy system designs. However, even when considering a farm powered by renewable energy sources, it is worth considering the environmental impacts and land use requirements to facilitate energy generation. This would enable more accurate analysis. Moreover, techniques are being developed in industry to reduce energy use considerably, such as recycling waste heat or improving energy efficiency through direct-current electricity use and improved lighting designs. A validated life-cycle assessment considering a state-of-the-art closed-PFAL is needed to benchmark the potential to address the criticisms of environmental impact and energy use for VPF.

The study examining the drivers for DSS use in agriculture concludes that collaborative decision support functionality requires further exploration to learn about its value to farmers. There is little evidence that web applications with community data-sharing provide tangible benefits to their users. Moreover, a longitudinal study is required to see whether compliance-based software that addresses necessary regulations can catalyse technology adoption in technology-averse farmers. Data collection can be labour-intensive, and it can often take second priority unless data is automatically collected. It is essential to develop sensor infrastructure that can minimise data collection time. It is worth delegating the responsibility to particular employees to keep records and utilise data that aligns with business goals. This is not unique to field-based farms, as many vertical farms interviewed in the lessons learned study did not collect the data necessary to build an operational history demonstrating improvement.

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APPENDICES

A. ECONOMIC ANALYSES CAPITAL AND OPERATIONAL COSTS BREAKDOWN

In Section 2.6.1, VPF economic analyses are reviewed. The models and their case studies were examined by classifying and extracting the data for breakdowns of capital costs and operational costs alongside their production output. This enabled identification of missing values, anomalies, research gaps, and comparison where possible.

A.1 CAPITAL COSTS BREAKDOWN

In Table S1, a breakdown of CapEx is shown from economic analyses in Table 2.6

Table S1. CapEx proportional breakdowns across different analyses for vertical plant farms.

VPF Analyses	[90][E,P,H]	[85][E,P,H]	[91][E,P,H]	[36][U,H]	[120,188][U,H]
Label ID:	A	B	C	D	E
Year	2016	2018	2020	2014	2022
Classification	Semi-closed-PFAL		Closed-PFAL	Vertical hybrid farm	Container farm
Size (m^2)	50	279	225	2,500	29.8
No. of tiers	4 layers	6 layers	6 layers	37 storeys	4 layers
Crop type	Basil	Lettuce	Basil	Mix	Basil
Yield (kg/year)	6,000	14,900	33,800	3,570,000	2,,780
Building cost breakdown (%)					
Building refurbishing (%)	13	-	-	-	-
Building use permit (%)	2	-	-	-	-
Infrastructure (%)	-	8.34	8.6	-	-
Total building (%)	15	8.34	8.6	55.3	-
Equipment cost breakdown (%)					
HVAC (%)	8	0.88	0.71	-	-
Growing system (%)	12	31.3	11.4	-	-
Racking system (%)	-	-	13.2	-	-
Seeding (%)	-	-	-	-	-
Sensors (%)	4	-	-	-	-
Lighting (%)	30	46.1	55.5	-	-
CO_2 supply (%)	1	-	-	-	-
Contingencies (%)	13	-	-	-	-
Other (%)	17	13.4	10.5	-	-
Total equipment (%)	65	91.7	91.4	44.8	100
Total costs					
Total CapEx (£)	8,700-26,100	422,000	278,000	176M	99,700
CapEx (£)/m^2	174-522	1510	1,240	70,200	3,352
CapEx (£)/kg/year	1.45-4.35	28.3	8.29	49.1	35.9

[U] Converted USD to GBP using the exchange rate in February 2021 (1 USD = 0.72 GBP)

[E] Converted EUR to GBP using the exchange rate in February 2021 (1 EUR = 0.87 GBP)

[P] Claimed to be profitable

[H] Claimed to be profitable

A.2 Operational Costs Breakdown

In Table S2, a breakdown of OpEx is shown from economic analyses in Table 2.6.

Table S2. OpEx proportional breakdowns across different analyses for fixed and variable costs.

VPF Analyses	[85][U,P,H]	[90][E,P,H]	[115][U,H]	[91][E,P,H]	[102][U,H]	[36][E,H]	[86][U,P]	[62][U,P]
Label	A	B	C	D	E	F	G	H
Classification	Semi-closed-PFAL		Closed-PFAL		Mixed PFSL-PFAL hybrid	Vertical hybrid farm	Aggregated Mixed PFALs	
Size (m^2)	279	50	N/A	225	2,625	2,500	N/A	N/A
Crop type	Lettuce	Basil	Lettuce	Basil	Mix	Mix	Lettuce	Mix
Yield (kg/year)	62,531	3432	N/A	33,750	1.025M	3.573M	N/A	N/A
Fixed cost breakdown (%)								
Rent	3.60	0.28	-	4.7	-	-	1	27 with utilities
Distribution	-	8	9.8	-	-	-	6	6
Depreciation (%)	-	12	21	After	-	-	23-30	-
Salaries	In wages	-	-	-	-	-	-	-
Tax	-	8	-	-	-	-	-	-
Variable cost breakdown (%)								
Seeds (%)	5.30	3.23	2.1	4.6	15	1	2	3
Consumables (%)	8.4	9.56	7.6	0.4	1%	5%	7-20	8-
Packaging (%)	13.20	-	-	1.7	-	-	-	27 with rent
Water (%)	0.50	1.08	-	0.6	1	-	-	
Energy (%) HVAC	0.4	39	21	10.7	42	67	21	
Energy (%) Lights	25.5			41.8				
Wages of direct labour (%)	43.10	9	28	35.1	13	26	26	56
Other (%)	-	10.14	10.5	0.04	-	2	14	-
Total costs								
Total OpEx (£)	149,404	N/A	N/A	131,021	6.26M	6.98M	N/A	N/A
OpEx (£)/m²	536	N/A	N/A	582	2,385	2792	N/A	N/A
OpEx (£)/kg	2.39	-	-	3.88	7.73	1.95	-	-

[U] Converted USD to GBP using the exchange rate in February 2021 (1 USD = 0.72 GBP)

[E] Converted EUR to GBP using the exchange rate in February 2021 (1 EUR = 0.87 GBP)

[P] Claimed to be profitable

[H] Claimed to be profitable

B. Financial Model Method Statement

The financial risk method is first presented in Section 3.5.3. Following the publication of that chapter, the method was expanded and then modelled using Python programming language with Microsoft Excel. In Section 6.4, the next iteration of the model and the results from executing it on two case-studies are presented. In this section, the model framework alongside its assumptions, equations, and risk quantification are described in detail.

B.1 Economic Model Breakdown

The model functions through a series of modules that interprets inputs based on the local market, selected crops, farm characteristics, labour, consumables and more. It calculates revenues and costs such as capital expenditure (CapEx), Operational expenditure (OpEx) and cost of goods sold (COGS) for resulting return on investment (ROI). This information is collected from a series of detailed business planning spreadsheets (Current_Financial_Model.xlsx). These spreadsheets were adapted from a business planning template for urban farms (adapted with permission from Agritecture [269] 2022) that encouraged users to make assumptions about their farm and build a financial model for year 1 and year 2 of production. Current_Financial_Model.xlsx has been developed as a graphic user interface that collects user inputs and decisions (growing system, lighting type, customer selection, environmental control levels). The information is processed from the spreadsheets into the Python script (main_pba.py) which runs probabilistic computations for 15-year cashflow projections and risk assessments relevant to the farm type. The resulting analysis is a 15-year cash flow projections as depreciation for a vertical farm is approximately 15 years [115).

To illustrate how the model functions to compute risk profiling, Figure S1 shows the simplified flow of computation from left to right, whilst omitting the interdependencies inherent in plant growth. The diagram is labelled with numbers 1 to 12 which will be explained through a series of equations S1 through to S12.

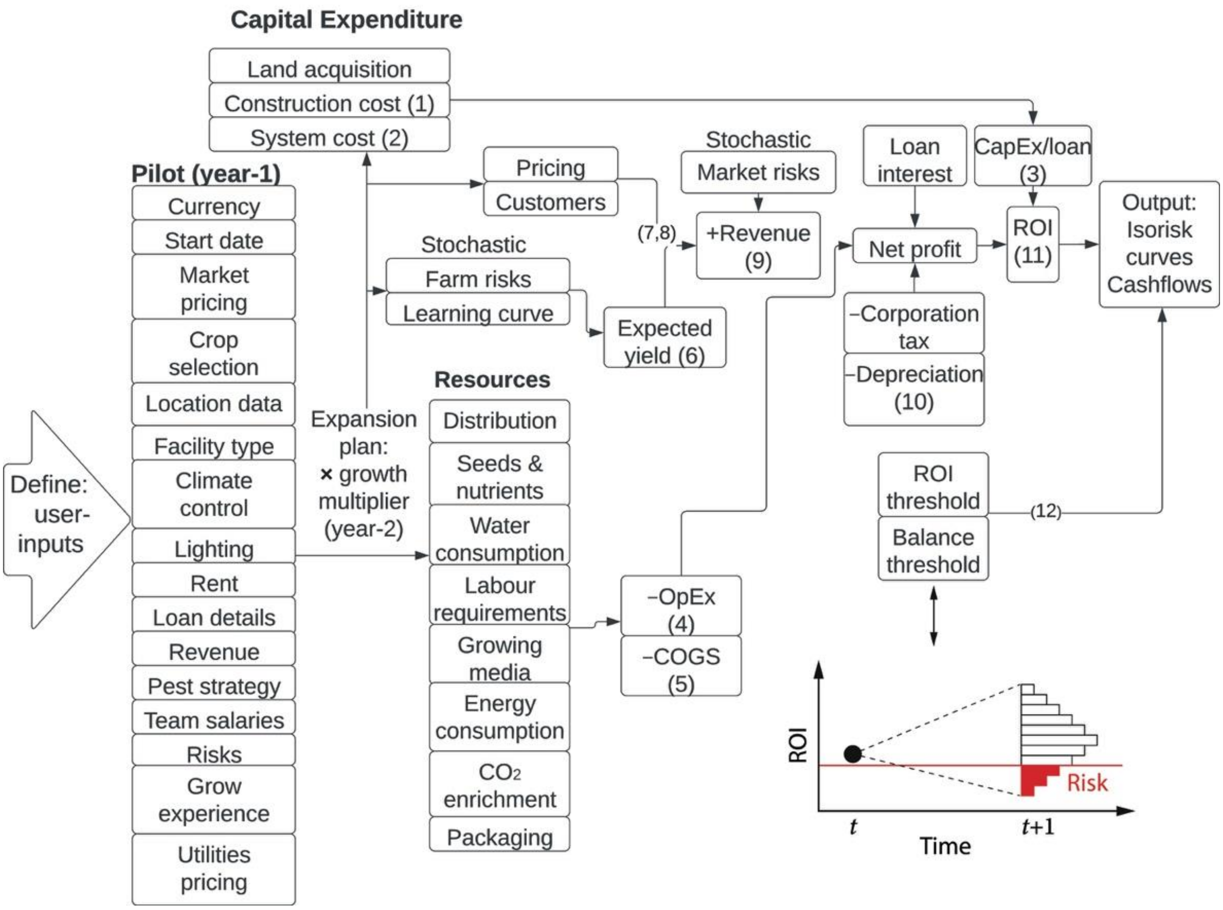

Figure S1. Financial risk model structure (flow left to right) utilising Equations S1 to S12

Equation (S1 calculates the construction cost of a VF based on the defined farm characteristics for both a pilot farm production and a scaled-up production. Exact values can be used (if known), otherwise an interval can be used or generalised costs in the specified currency for several locations based on Shao et al.'s study [76] on economic estimation for vertical farms. Financial_Model_Template_v2.xlsx within the model library is used to compute the default generalised cost based.

$$\text{Construction costs} = \text{Structure} + \text{Finishing} + \text{Appliance} + \text{Land acquisition} + \text{Management} + \text{Building permit use} + \text{Electrical infrastructure} \quad \text{(S1)}$$

Equation (S2 calculates the system costs comprising of all the technology elements required to operate a vertical farm and enabling it to grow produce. This also applies to both pilot and scaled-up production. Ideally the exact values are known by the user, otherwise a range can be provided if a budget is given, then values will be allocated through a percentage breakdown similar to previous examples given in Table 6.1. of the main article.

$$\text{System costs} = \text{Cold storage} + \text{Lighting system} + \text{Growing system} + \text{Racking} + \text{Germination \& clean area} + \text{Irrigation and nutrient system} + \text{Processing plant} + \quad \text{(S2)}$$

Waste management + Renewable energy supply + Heating, ventilation and air-cooling (HVAC) + Sensors + CO_2 supply

Equation (S3 calculates CapEx by summing the total construction and system costs. This cost is deducted from the working capital that will constitute the funding required to develop the farm (i.e. the initial working capital and any loans or grants). If a loan is involved, the amount is stated in the inputs with loan tenure and interest rate.

$$\text{CapEx} = \text{Construction cost} + \text{Systems cost} \tag{S3}$$

Equation (S4 calculates the fixed costs as OpEx either from user-inputs, or from generalisations based on crops, business model, funding mechanism and farm-type.

$$\text{OpEx} = \text{Rent} + \text{Salaries} + \text{Insurances} + \text{Distribution} + \text{Other costs} \tag{S4}$$

Equation (S5 calculates the variable costs as cost of goods sold (COGS). The parameters are determined by consumable costs and direct labour attributable to farm operations based on wages and hours worked. Labour outputs will be affected by the experience of the farmer, this is reflected in the increased yield or drop in learning curve and not the cost of labour.

$$\text{COGS} = \text{Direct labour} + \text{Growing media} + \text{Packaging} + \text{Seeds \& Nutrients} + \text{Electricity} + \text{Water} \tag{S5}$$

The yield of a particular plant per annum is estimated by Equation (S6 and has been adapted from 'VFer' (see [76]) to factor the levels of control in the farm for nutrients, climate control, light control, growing experience and risk.

$$Y_a = Y_s \times A_G \times L_f \times \ CO2_f \times T_f \times N_f \times (1 - F_r) \ \times R_f \tag{S6}$$

The adjusted plant yield (Y_a) for a plant is calculated from the standard yield (Y_s) which is an estimated best case yield grown hydroponically in selected system (kg per square-metre of growing area), multiplied by the growing area (A_G) and various factors influencing its value [76]. The factors influencing yield include:

1. Light factor (L_f) – Light control is determined as 'High', 'Medium' or 'Low' based on PAR delivered to the plants' canopy to theoretical PAR requirements. Adapted to include light spectra, which has been found to influence crop productivity more than PAR requirements according to industry leading grow light developers [268]. With artificial lighting, this value should be 1 if lighting is controlled at optimal level for plant growth. This value is set as 0.9 with suboptimal lighting and 0.6 with low lighting control.
2. CO_2 factor (CO_{2f}) – This is a Yes/No input. The reduction multiplier of yield from insufficient CO_2 enrichment is 0.9. If sufficient CO_2 is added this value is 1.
3. Temperature factor (T_f) – This is the reduction of yield caused by overheating or freezing of the grow area, especially if the farm is uncontrolled by HVAC or other

systems. Value is set at 0.9 for preliminary estimation [76], but is assessed depending on the climate, level of HVAC control and the crop requirements. Value is set at 0.9 for 'medium' control for preliminary estimation. 'High' HVAC control provides a value of 1, and low control provides 0.85.

4. Nutrient factor (N_f) −The reduction of yield caused by inadequate nutrient intensity or mismatched nutrient composition. 'High' value is set at 1 when individual sump tanks and nutrient solutions are tailored to the crop with automatic control. 'Medium' value is 0.9 for nutrients considered for crops, but sumps are not for different for crop types and there is automated control. 'Low' is an off the shelf nutrient solution for general hydroponic use at 0.85. Depending on level of specific nutrient control and whether the farm has automated dosing in place, this value may change.
5. Failure rate (F_r) – The failure rate of crops is influenced by wastage from mishandling, unsellable or damaged crops. This decreases exponentially with time as farm operators overcome the learning curve with growing as evaluated by Agritecture [84]. Growing experience is categorised as 'High', 'Medium' or 'Low' for hydroponic growers with 5-10, 3-5, 0-3 years of experience respectively. This parameter varies from 3-12% depending on experience (see Figure S2) and is much lower than found elsewhere [76,84] as this model considers other sources of waste associated with the risk factor described. This failure rate requires validated research analysing crop yield increases through data analysis on a commercial farm.
6. Risk factor (R_f) –The risks factor parameter represents issues that could destroy or damage a harvest requiring a deep clean of the farm. Examples would include pest outbreaks, plant pathogens or compliance issues. This parameter is random but reduced when precautionary measures are implemented that mitigate the risk. A list of risks is provided in the risk section with associated distributions.

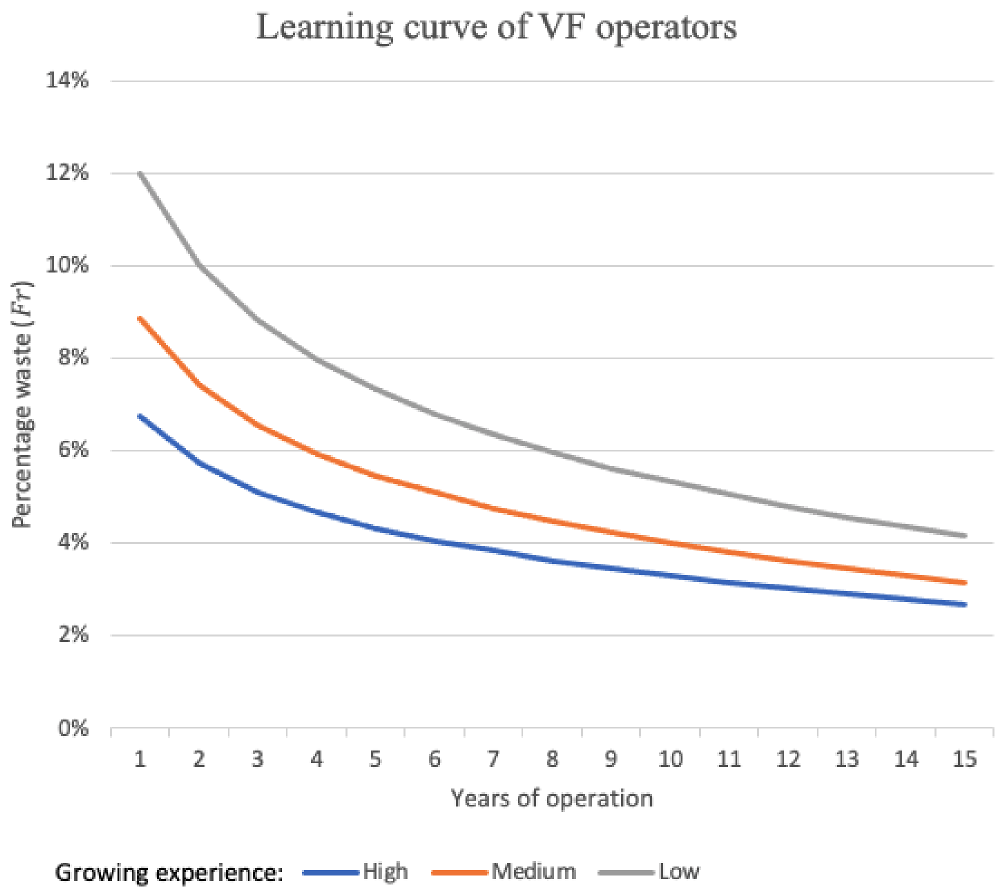

Figure S2. Learning curve of farm operators displaying wastage rate over years of operation (adapted with permission from [84]).

The annual income for a selected crop type is calculated by Equation (S7. This has been adapted from [76] to include different customer segments.

$$PI_c = P_p \times P_i \times Y_a \times PSR \times CSR \tag{S7}$$

The plant income per plant for a customer segment is calculated by multiplying the following parameters by the adjusted yield computed from Equation (S3:

1. Plant price (P_p) - The cost of the crop in the local market which is user-defined from market research.
2. Plant index (P_i) - The ratio that the price of products from the vertical farm are sold for compared to the average market price of the crop. Set at 1.25 if not specified by the user and based on claims that a farm can sell produce 20-30% higher than market price [69]. Crop pricing is extremely dependent on the local market and quality of produce. If the price is specified by the farm, a value can be manually replaced.
3. Adjusted yield (Y_a) as defined in Equation (S6.
4. Customer share ratio (CSR) – The crop may be sold to customers at different price brackets, such as wholesale or retail for example. This ratio represents the

proportion of customers sold to at the price bracket or for a particular crop. Vertical farms typically spread their market across a couple of customer segments.

The sum of all annual crop incomes are combined for a total PI in Equation (S8. This equation is the summation of all the sources of income for each plant species, denoted as ACI, and their associated customer segments denoted by c.

$$ACI = \sum_{c=1}^{cust.} \sum_{x=1}^{spec.} PI_{c,x} + = \begin{pmatrix} PI_{cx} \\ \vdots \end{pmatrix} \tag{S8}$$

Equation (S9 is the total annual revenue, a sum of annual incomes with alternative revenue streams (value-added products (VAP), education, tourism, hospitality and grants) which are uniquely specified and multiplied by a predicted growth factor every year.

$$\text{Revenue} = ACI + VAP + \text{Education} + \text{Tourism} + \text{Hospitality} + \text{Grants} \tag{S9}$$

Depreciation is computed in Equation (S10 by utilising the default lifespan values proposed by Kozai & Niu [115]: 15 years for the building and 10 years for the equipment (system costs except for lighting). Light-emitting diode (LED) lighting depreciation is dependent on the lifespan (hours of use) from the lighting systems data from manufacturers and photoperiod required by plants. LED lifespan is multiplied by 0.8 as light quality will be degrade sooner than total lifespan rendering the equipment obsolete although this requires further research. The lifespan for all elements can be changed by the user.

$$\text{Depreciation} = \frac{\text{Equipment}}{10} + \frac{\text{Structure} + \text{Finishing} + \text{Appliance}}{15} + \frac{\text{Lighting}}{\text{Lifespan} \times 0.8 \div \text{Average Photoperiod}} \tag{S10}$$

Equation (S11 calculates ROI by calculating net profit divided by total investment (CapEx), and then multiplying by 100 for a percentage. The net profit is calculated as the revenue subtracting OpEx, COGS, loan repayments (with interest) and taxes associated with the specified operation. The model can then compute the projected cashflows for 15 years with ROI, payback period and other key financial metrics.

$$\text{ROI} = \frac{\text{Revenue} - \text{OpEx} - \text{COGS} - \text{loan repayments} - \text{Depreciation} - \text{Tax}}{\text{CapEx}} * 100 \tag{S11}$$

After using the equations listed above within the model to calculate the cashflows, a required financial balance and ROI threshold can set by the user (which can increase with time) which will be used for the risk profile of insolvency. For ROI, a venture capitalist would typically look for a return of 10-20%+ [77]. The threshold for ROI may vary with time according to investor demands. The default quasi-insolvency thresholds are defined as cashflow becoming negative (T_B) and an ROI under the following thresholds (T_{ROI}):

- Year 0: Below 10% ROI
- Year 3.5: Below 0% ROI
- Year 7: Below 10% ROI

The companies under analysis within this article are at risk of insolvency when they have no capital runway, which means they will collapse if they do not raise additional capital whilst their revenues and expenses remain unchanged. The probability of insolvency for a given year (INS) is therefore defined in Equation (S12.

$$P(INS) = P[\,(B < T_B)\ \&\ (ROI < T_{ROI})\,] \tag{S12}$$

The p-box described within the article represents all the possible scenarios modelled and probabilities of bankruptcy. The resulting risk analysis can be made useful by introducing categories defined by probability of bankruptcy over some defined time scale:

- *Critical:* 50% probability of bankruptcy within 3 years
- *Substantial risk:* 25% probability of bankruptcy within 5 years
- *Moderate risk:* 10% probability of bankruptcy within 10 years
- *Safe:* Less than 10% probability of bankruptcy within 10 years

B.2 MODEL ASSUMPTIONS

The economic model makes assumptions for most of the default parameters that draws upon data based on existing analyses and books. Values can be easily manually overwritten through the business planning spreadsheet used for this analysis by overwriting cells when information is known or an interval can be provided if unknown. A list of the assumptions in the model is provided in Table S3.

Table S3. Model assumptions

Element	Assumption	Reference
Pilot farm to full-scale production	The first year of analysis is based on a pilot farm that upgrades in size from the second year by a factor of the growth multiplier.	-
CapEx estimates	CapEx estimates are provided through typical costs and broken down into component costs through proportions aggregated in the literature review. To compensate for inaccuracies, users can incorporate ranges or add their exact values.	[76]
Growth multiplier	The growth multiplier is used to multiply growing area from pilot to full-scale production. In the absence of any further data the model will extrapolate other parameters such as yield and utility costs (electricity, water) by multiplication with growth multiplier.	-
Quantity of light	The number of light fixtures is dependent on the	-

fixtures	system type and therefore is required to be input manually.	
Heating, ventilation and air-cooling (HVAC) energy consumption	If HVAC energy consumption is unknown then the calculation for energy consumption is calculated by multiplying light energy consumption by 1.25 to accommodate for HVAC, pumps, fans, and so on, based on lighting typically accounts for 80% of energy costs.	[76,409]
Utility costing	Utility costing is calculated by estimated consumption multiplied by pricing.	-
Depreciation	15 years for the building and 10 years for the equipment (except for lighting which is depreciated based on lifetime by supplier.	[115]
Best-case yield estimates	The built-in database provides default values of best-case net yield of different crop types and system configuration (nutrient-film technique, deep water culture, drip tower, etc.) is based upon non-validated greenhouse data. Users are encouraged to be replace these. Yield data for vertical tower systems is sourced from the inventor's PhD thesis which is also used in other analyses. For the UK case study, a normal distribution was created, N(45,2) taking into account expected yield and the lack of yield tracking practices. For the Japanese case study, 61 kg per m2 was used.	[193,206,208)
Adjusted crop yield	Adjusted crop yield estimation is based upon net yield per unit growing area and is reduced by various factors (temperature, light, CO_2, etc.) however in reality plant growth is much more nuanced with interdependencies that are difficult to estimate.	[146,412]
Crop risks	Crop risks are influenced by strategic decisions on pest management, level of climate control and level of biosecurity (described further in Section B.3). These require further research to be validated. The risks can be toggled on and off by the user.	-
Market conditions and risks	By default perfect-market condition implies that competitive prices and wages exist for all goods and services in all possible contingencies. Market risks can be toggled on and are influenced by business model type and sales (described further in Section A.3).	-
System specifications	System specification data (growing systems and LED fixtures) are based upon brochures from suppliers.	[187]

B.3 Risks

In this section, how risks and represented in the model will be described. A list of risks will then be described, followed by a breakdown of the risks considered within the analysis conducted on both case studies and how they are influenced by certain farm characteristics.

How risks are represented

Currently, the model adjusts the probability and impact for a risk based on farm characteristics. An example reflective of risks in the model is provided for an arbitrary pest outbreak probability (P) within a given year in Equation (S13. The level of climate control ('high' providing the exact climate humidity, airflow and temperature desired, 'medium' providing roughly the required climate control although there is some fluctuation, and 'low' being little or no system in place). Pest detection technology also influences the probability, as catching an outbreak early could prevent a farm-wide breakout. The probabilities for a pest-outbreak are represented as an interval. The impact (I) is then provided in Equation (S14 there are two scenarios: with a pest management strategy or without. The impact is the risk factor (R_f) (see Equation (S6) multiplied by the adjusted yield. In this case, we do not know the distribution of impact, so it is assumed the risk factor is a beta distribution, with parameters in 15 ≤ a ≤ 60 and 1 ≤ b ≤ 5 for no pest management strategy, and 60 ≤ c ≤ 120 and 0.5 ≤ d ≤ 5, for a pest management strategy. Bounding beta distributions in this way has been used by researchers at NASA for reliability analysis [410].

$$P(\text{Pest}) = \begin{cases} \text{climate control} = \text{'High' or pest detection} = \text{"Yes"} & 0.5 - 2\% \\ \text{climate control} = \text{'Medium' or pest detection} = \text{"No"} & 5 - 15\% \\ \text{climate control} = \text{'Low'} & 25 - 75\% \end{cases} \quad \text{(S13)}$$

$$I(Pest) = \begin{cases} Y_a \times \text{Beta}(a, b) & \text{No pest management} \\ Y_a \times \text{Beta}(c, d) & \text{Pest management} \end{cases} \quad \text{(S14)}$$

List of risks

The risks, uncertainties and opportunities (explored in Section 6.3.5) were incorporated within the model and are defined in Table S4 They are supported from references in the literature and interviews conducted with the purpose of eliciting data [146]. The insights gleaned from interviewing operating and shuttered farm operators informed the causes and associated probabilities and impacts [69]. As each farm is a unique case, it is suggested that the user of the analysis fills in the 'Risk' sheet embedded within the Financial_model_template.xlsx to create a risk register. The risks and associated impacts and probabilities are required to be manually programmed into "risk_pba.py". It is important to note that the default values contained within the case studies are non-empirical and were based on anecdotal reports. Quantitative data was not collected as most vertical farms do not have established protocols to log risks events. Probability values, associated impact, and frequency were therefore estimated using bounds to improve accuracy. It is suggested that risks and opportunities are adjusted by the user after creating a risk register for the project under analysis. These risks can be toggled on and off. Further research and collaboration is required across the sector to refine such estimates, providing historical and empirical values.

Table S4. Risks that can be considered in economic analysis

Description	Cause	Potential impact	References

Pathogen outbreak	Low grower experience, low climate control, low biosecurity	Reduction of annual adjusted yield	[69]
Small or big repair	After 2 years, increases with automation level	Repair cost as a fraction of system cost	[71,78]
Customer withdrawal	Dependent on business model (retail, wholesale, hybrid). Also influenced by competitors in the market place.	Deduction of annual crop income	[69]
Pest outbreak	Low insulation level, low climate control, no integrated pesticide management	Reduction of annual adjusted yield	[69]
Electrical blackout	Aeroponic system without a backup generator. Dependent on location	Reduction of annual adjusted yield (one crop cycle's worth of harvest)	[269]
Labour challenges	Low automation level and lower probability in starting years	Either a reduction of adjusted yield due to damaged product or extra labour cost	[69,78]
Funding not acquired	Reliant on acquiring extra funding (grant, loan, etc.)	Expected funding specified in cashflow is not acquired and delayed 1-3 years.	[42,69]
Wastage rates	Dependent on growing experience	Low experience: Medium experience: High experience:	[69,78,269]
Zoning code and regulatory obstacles	Project is delayed and farm cannot be scaled or built within first/second year	No annual crop income until approved but salaries are a continued expense	[69,78,214,269]
Improved labour efficiency	Implementation of manufacturing principles	Potential 2-8% reduction in labour each year resulting in ~50% labour cost reduction after 7 years	[63,205]
Improved electrical efficiency	Improvements in energy conversion.	Potential 1-3% reduction in lighting energy cost per year	[63]
More efficient LED lighting	New LED lightings acquired after depreciated period	10-40% energy efficiency boost after replacement	[63]

Pathogen Outbreak

The risk is a probability bounds mixture that combines probability and impact. It is then multiplied by yield as a risk factor (R_f) described in Equation (S6. Table S5 shows the pathogen outbreak risk probabilities and impacts.

Table S5. Pathogen outbreak risk table

Priors	Probability per period	Impact
Biosecurity level = 'high'	5%/year	Minimum = 5% of yield Maximum = 15% of yield Mean = 7% of yield Standard deviation = 2.5% of yield
Biosecurity = 'medium'	10%/year	
Biosecurity = 'low' or Climate control = 'low'	20%/year	
Biosecurity = 'low' and Climate control = 'low'	25%/year	

Pest Outbreak

The risk is a probability bounds mixture that combines probability and impact. It is then multiplied by yield as a risk factor (R_f) described in Equation (S6. Table S6 shows the pathogen outbreak risk probabilities and impacts.

Table S6. Pest outbreak risk table

Priors	Probability per period	Impact
Climate control = 'high' and Insulation level = 'high' and pest detection = 'Yes'	0.5%/year	With integrated pest management plan: Minimum= 0.1% of yield Maximum = 10% of yield Mean = 3% of yield Standard deviation = 1.5% of yield Without integrated pest management plan: Minimum= 5% of yield Maximum = 20% of yield Mean = 8% of yield Standard deviation = 3% of yield
Climate control = 'high' or Insulation level = 'high' and pest detection = 'No'	5%/year	
Climate control = 'Medium' or Insulation level = 'Medium and pest detection = 'No'	20%/year	
Climate control = 'Low' or Insulation level = 'Low' and pest detection = 'No'	35%/year	
Climate control = 'Low' and Insulation level = 'Low' and pest detection = 'No'	40%/year	

Power Outage

The risk is a probability bounds mixture that combines probability and impact. It is then multiplied by yield as a risk factor (R_f) described in Equation (S6. Table S7 shows the power outage risk probabilities and impacts.

Table S7. Power outage risk table

Priors	Probability per period	Impact
No electrical back-up and aeroponic system	1%/year Location specific	Minimum = Loss of 100% of one month's harvest Maximum = Loss of 100% of two month's harvest Mean = 75% of two month's harvest Standard deviation = 0.02
Any other scenario		None

Repairs

The risk is a probability bounds mixture that combines probability and impact. It is then multiplied by capital expenditure for facility and lighting costs. Table S8 shows the repairs risk probabilities and impacts.

Table S8. Repairs risk table

Priors	Probability per period	Impact
Automation level = 'High'	Small repairs = 30% per year Big repair = 2% per year	Small repairs: Minimum = 0%

Automation level = ‘Medium’	Small repairs = 25% per year Big repair = 1% per year	Maximum = 3% Mean = 1.5% Standard deviation = 0.5% Big repairs: Minimum = 1% Maximum = 10% Mean = 4% Standard deviation = 2%
Automation level = ‘Low’	Small repairs = 20% per year Big repair = 0%	

Lighting efficiency improvements

LED lighting are a dramatically redefining the economics of vertical farming. The lighting efficiency (i.e. the light emitted per unit of energy) and their lifespan has doubled roughly every year since 2010 [411]. Lighting systems are assumed to be replaced after the lifetime has elapsed and paid with the depreciated costs accounted. Due to the rapid improvement in LED efficiency, it is an important opportunity to consider. In this analysis, upon the elapsed lifetime the wattage of the new lighting solution is changed to 50 to 80% with a best-guess estimate of 65% of the previous system.

Other Risks and Opportunities

There are other risks and opportunities that can be considered depending on what the user would like to consider. These include:

- Withdrawal of a customer
- Planning delays
- Labour challenges
- Labour efficiency improvements

These can be found within the model risk_pba.py and can be toggled on and off. There are omitted due to the excessive uncertainty displayed when considering all risks, rendering the results obsolete. When examining risks and opportunities it is worth toggling them on and off sequentially to observe how they affect the results similar to sensitivity analysis.

B.4 Summary

The method described in this paper assesses economic viability and financial risk despite the lack of available production and financial data. In addition, it can be used to inform improvements in farm design towards profitable business models. The financial risk analysis model can be found at: https://github.com/GaiaKnowledge/VerticalFarming as a part of a wider decision support system project [146]. It utilises probability bounds analysis combined with first-hitting-time which has been used for other disciplines in ecology and engineering [404]. This novel method is applied to both real-life (UK) and hypothetical (Japanese) vertical farms.

C. FINANCIAL MODEL SUPPLEMENTARY DATA

Supplementary data for the financial model results (Chapter 6) is separated into two sections, UK and Japanese case study. The data for each study includes full-tables for farm characteristics, capital costs and operational costs. These are included within a model inputs table that were the direct inputs to the financial risk model. The UK case study also includes a suggested interventions subsection that notes the modifications to inputs.

C.1 UK CASE STUDY

The UK case study data is contained within a spreadsheet called 'Current_Financial_Model_FU_v1.xlsx' in the model library which is executed by the model script: main_pba_UK_Farm.py. The pilot and full-scale production are considered by the model and are therefore detailed within the tables for this section.

Farm Characteristics

UK Farm characteristics are detailed in Table S9.

Table S9. Farm characteristics for the pilot and full-scale UK farm

Characteristic	Pilot production (year 1)	Full production (year 2)	Unit
Real Estate			
Facility size	220	220	m2
Facility height	3	3	m
Space utilisation	27	27	%
Growing space	59	119	m2
Systems			
Growing system	ZipGrow Racks, 8' towers	ZipGrow Racks, 8' towers	
Grow levels	30 towers per rack	30 towers per rack	
Number. of racks	8	16	
Stacked growing area	196	392	m2
Number of lights	128	256	
Lighting system	Intravision Spectra LED Blade Single Sided	Intravision Spectra Blade Single Sided	
Light wattage	100	100	W
Energy price	0.073-0.108	0.073-0.108	£/kWh
Water price	0.002	0.002	£/L
Annual electrical consumption	127,170	224,255	kWh
Labour			
Number of direct labourers	2	3	people
Number of indirect staff	1.5	3	people
Direct labour hours per week	20	20	hours per person
Direct hourly cost	9.50	9.50	£/hour
Crop: Lettuce			
Annual yield	3,900-5,500	8,800-10,800	kg/year
Harvest weight	0.1	0.1	kg
Photoperiod	16	16	hours

Product 1 weight	0.3		0.3	kg
Customer segmentation	85	15	-	% to customers
Unit prices	7.50	3	-	£/unit
Packaging cost	1.50		0.85	£/unit
Attributes*				
Business model	Hybrid		Wholesale	
Grower experience	Medium		High	
Automation level	None		Medium	
Climate control level	Medium		High	
Lighting control level	Medium		High	
Nutrient control level	Medium		High	
CO_2 enrichment	No		Yes	
Biosecurity level	Medium		High	

*Definition of input is detailed in method statement in the supplementary material

Capital Costs

The capital costs for both the pilot and scaled-up production are detailed in Table S10.

Table S10. Pilot and full-scale farm data for UK case study

Capital costs	Pilot farm (year 1)	Full-scale farm (year 2)	Total	Unit
Construction				
Structure	0	0	0	£
Finishing	350	3,500	3,850	£
Appliance	750	3,500	4,250	£
Management costs	3,600	5,429	9,029	£
Electrical infrastructure	5,520	2,500	8,020	£
Real estate	0	0	0	£
Total construction costs	10,220	14,929	25,149	£
Systems				
Growing system cost	28,296	32,775	55,071	£
Lighting system cost	37,440	49,725	87,165	£
HVAC system cost	700	2,000	2,700	£
Miscellaneous cost	9,548	2,000	9,548	£
Total equipment cost	67,984	86,500	154,484	£
Total capital costs	78,204	101,429	179,633	£

Operational characteristics and costs

The operational characteristics and costs are detailed in Table S11. These values are reflective of Table 6.6 in the main manuscript.

Table S11. Operational characteristics and costs

	Pilot VF	Full-scale VF	Unit
Grants and other funding	89,000	128,000	£
Operational Expenditure			
Rent	0	0	£/year
Staff costs (non-direct labour)	60,750	83,214	£/year
Insurance	1,551	1,551	£/year
Distribution	27,860	31,594	£/year

Other costs	729	1346-5,980	£/year
Total OpEx	75,210	108,998	£/year
Cost of goods sold			
Direct labour staff	2	3	No. of people
Wages	19,758	29,637	£/year
Growing media	1,255-1,752	2,509,-3503	£/year
Seeds and nutrients	3,628-7674	7,255-15,344	£/year
Total electricity cost	9,340-13,731	15,929-23,416	£/year
Water consumption	7358-10272	14713-20539	L
Water price	0.002	0.002	£/L
Water cost	30-190	60-381	£/year
Total COGS	53,787-70,839	78,371-104,362	£/year
Other fixed costs			
Depreciation and Amortisation	10,208	20,417	£/year
Tax rate	0	0	%
Working capital	197,000	63,409	£
Loan amount	158,000	-	£
Loan tenure	7	5	years
Loan interest	5	5	% per year

Model inputs

The inputs to the model are detailed in Table S12 and can be found within the model library as "Current_Financial_Model_FU_v1.xlsx" on the inputs sheet. As the spreadsheet does not propagate uncertainty until processed by main_pba_UK.py, several lines of code manually input uncertainty:

```
scenario.electricity_price = minmaxmean(0.0734, 0.1079, 0.09065)
light_improvement = minmaxmean(0.5, 0.8, 0.65)
water_use = pba.mmms(1325, 8325, 3730, 2039)
```

Table S12. Model inputs from Current_Financial_Model_FU_v1.xlsx

#	Code	Input	Unit
1	start_date	01/02/2021	Date
2	facility_size_pilot	220	currency
3	percent_production_area_pilot	0.27	m^2
4	growing_levels_pilot	1	%
5	weight_unit	kg	%
6	growing_area_mulitplier	2	# of levels
7	no_lights_pilot	128	Weight unit
8	packaging_cost_pilot	£1.50	Multiplier
9	packaging_cost_full	£0.85	# of lights
10	other_costs_pilot	2.0%	£
11	farm_type	Basement	£
12	business_model	Hybrid	%
13	grower_exp	Medium	-
14	automation_level	Low	-

15	climate_control	Medium	-
16	lighting_control	Medium	-
17	nutrient_control	Medium	-
18	system_type	ZipRack	-
19	system_quantity	8	-
20	light_system	Intravision Spectra Blade Single Sided - J	-
21	growing_media	Rockwool	# of racks
22	ceiling_height	4	-
23	insulation_level	High	-
24	roof_type	Flat roof	Metres
25	co2_enrichment	No	-
26	structure_type	N/A	-
27	water_price	£0.002	-
28	electricity_price	£0.07	-
29	labour_improvement	5%	£
30	percentage_renewable_energy	0%	£
31	biosecurity_level	Medium	%/year
32	loan_amount	£158,000.00	%
33	tax_rate	0%	-
34	loan_interest	5%	£
35	loan_tenure	7	%
36	loan_type	Standard	%
37	crop_typ1	Lettuce (Farm Urban Mix)	Years
38	crop1_percent	100%	Type
39	crop1_system	Drip Tower	Crop type
40	crop1_harvest_weight	0.1	% of system space
41	crop1_product_weight	0.3	System type
42	crop1_customer_percent	85%	Kg
43	crop1_price1	£7.50	Kg
44	crop1_price2	£3.00	%
45	crop_typ2	Lettuce (Farm Urban Mix)	£
46	crop2_percent	0.0%	£
47	crop2_system	Drip Tower	Crop type
48	crop2_harvest_weight	0.1	% of system space
49	crop2_product_weight	0.45	System type
50	crop2_customer_percent	100%	Kg
51	crop2_price1	£9.50	Kg
52	crop2_price2	£0.00	% of system space
53	crop_typ3	Basil - Genovese	£
54	crop3_percent	0.0%	£
55	crop3_system	Drip Tower	Crop type
56	crop3_harvest_weight	0.075	%
57	crop3_product_weight	0.075	System type
58	crop3_customer_percent	100%	Kg

59	crop3_price1	£1.50	Kg
60	crop3_price2	£0.00	%
61	crop_typ4	None	£
62	crop4_percent	0%	£
63	crop4_system	Drip Tower	Crop type
64	crop4_harvest_weight	0.5	% of system space
65	crop4_product_weight	0.5	System type
66	crop4_customer_percent	0	kg
67	crop4_price1	£7.50	kg
68	crop4_price2	£7.50	%
69	vadded_products_multiplier	1	£
70	education_multiplier	1.15	£
71	tourism_multiplier	1.15	Multiplier per year
72	hospitality_multiplier	1	Multiplier per year
73	vadded_avg_revenue_y1	£ -	Multiplier per year
74	education_avg_revenue_y1	£-	Multiplier per year
75	tourism_avg_revenue_y1	£-	£/month
76	hospitality_avg_revenue_y1	£-	£/month
77	monthly_rent_y1	£-	£/month
78	monthly_distribution_y1	£2,322	£/month
79	monthly_rent_y2	0	£/month
80	monthly_distribution_y2	2632.853131	£/month
81	delivery_msalary	£1,500.00	£/month
82	farmhand_msalary	£1,500.00	£/month
83	parttime_wage	£9.50	£/month
84	ceo_msalary	£2,025.00	£/month
85	hgrower_msalary	£1,560.00	£/month
86	marketer_msalary	£2,025.00	£/month
87	scientist_msalary	£2,025.00	£/month
88	salesperson_msalary	£1,560.00	£/month
89	manager_msalary	£2,025.00	£/month
90	admin_msalary	£624.00	£/month
91	ceo_count_y1	0	£/month
92	hgrower_count_y1	0	£/month
93	marketer_count_y1	0.5	People
94	scientist_count_y1	0	People
95	salesperson_count_y1	0	People
96	manager_count_y1	1	People
97	delivery_count_y1	0	People
98	farmhand_count_y1	0	People
99	admin_count_y1	0	People
100	parttime_count_y1	173.32	Hours
101	ceo_count_y2	0	People
102	hgrower_count_y2	1	People

103	marketer_count_y2	1	People
104	scientist_count_y2	0	People
105	salesperson_count_y2	0	People
106	manager_count_y2	1	People
107	delivery_count_y2	0	People
108	farmhand_count_y2	0	People
109	admin_count_y2	0	People
110	parttime_count_y2	259.98	Hours
111	insurance_pilot	129.25	People
112	insurance_full	£129	People
113	capex_pilot	£78,204.00	People
114	capex_full	£179,633.00	£
115	capex_lights	£87,165.00	£
116	capex_facilities	£67,319.00	£
117	capex_building	£8,100.00	£
118	target_productivity_space	90	kg/m^2
119	target_productivity_energy	0.07	kg/kWh
120	target_productivity_labour	6	kg/man-hour
121	target_productivity_water	0.5	kg/L
122	target_productivity_nutrients	500	kg/kg
123	target_productivity_volume	130	kg/m^3
124	target_productivity_plants	800	No. of plants per m^2
125	target_productivity_CO2_emit	500	kg/kg
126	target_productivity_CO2_miti	50000	kg/kg
127	target_productivity_CO2_net	-1000	kg/kg
128	Integrated pest management	No	Yes/No
129	pest_detection	No	Yes/No
130	electrical_backup	No	Yes/No
131	currency	GBP	Currency
132	percent_production_area_full	27%	%
133	energy_type	Average UK energy mix	-
134	grants_rev_y0	89000	£
135	grants_rev_y1	128000	£
136	grants_rev_y2	0	£
137	grants_rev_y3	0	£
138	grants_rev_y4	0	£
139	grants_rev_y5	0	£
140	grants_rev_y6	0	£
141	grants_rev_y7	0	£
142	grants_rev_y8	0	£
143	grants_rev_y9	0	£
144	grants_rev_y10	0	£
145	grants_rev_y11	0	£
146	daily_energy_consumption	102.652383	kWh
147	other_costs_full	0.02	kWh

Results

Full result tables including probability bounds can be found in the model folder (https://github.com/GaiaKnowledge/VerticalFarming) as results_UK.xlsx. The graphs can be generated by executing the script 'main_pba_UK_Farm.py' Graphs for additional metrics not found in the main manuscript are shown in Figures S3-S11.

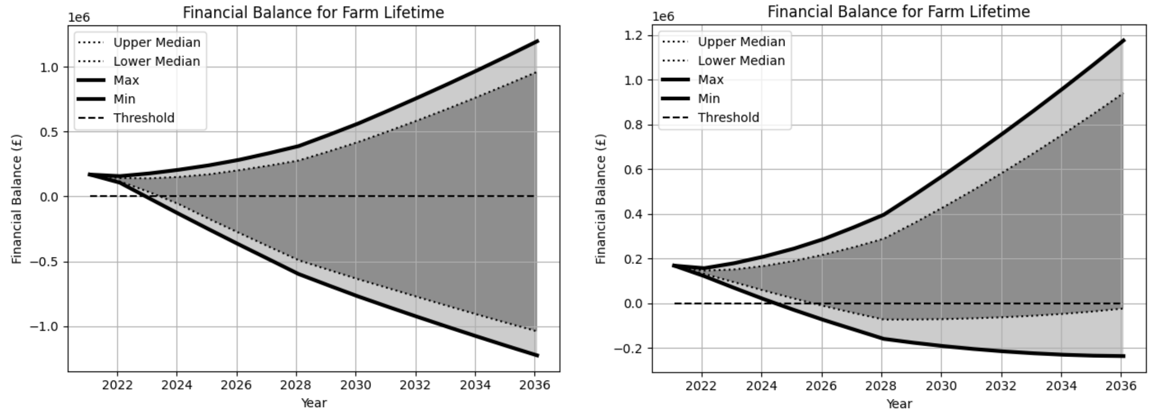

Figure S3. UK vertical farm financial balance with risk and opportunities (on the left) and without risk and opportunities (on the right).

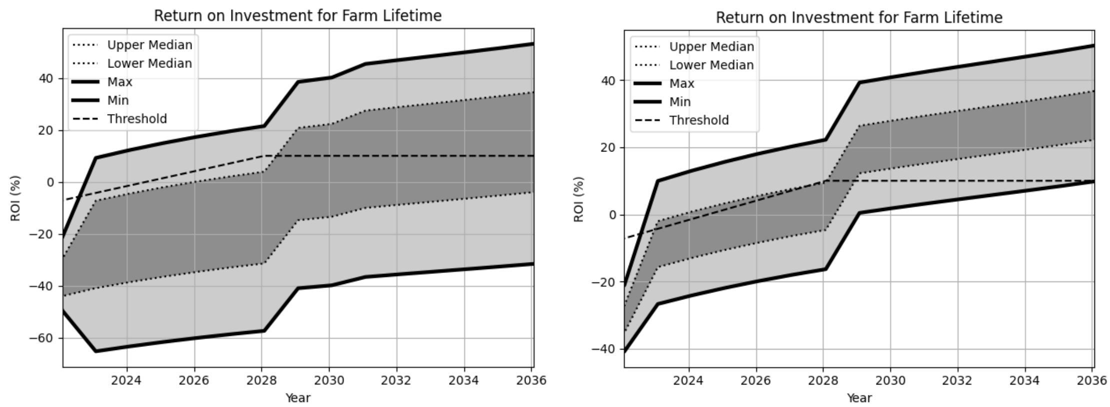

Figure S4. UK vertical farm return on investment with risk and opportunities (on the left) and without risk and opportunities (on the right).

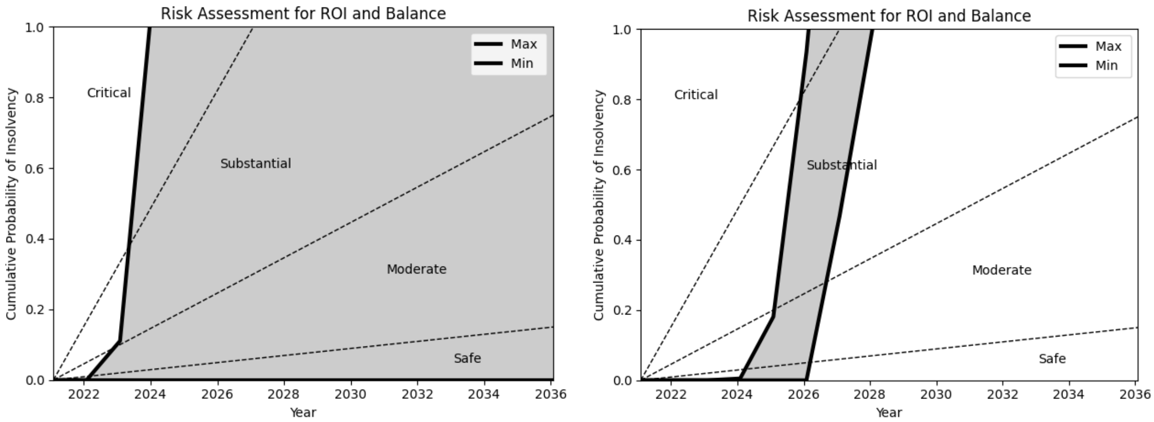

Figure S5. UK vertical farm risk profile with risk and opportunities (on the left) and without risk and opportunities (on the right).

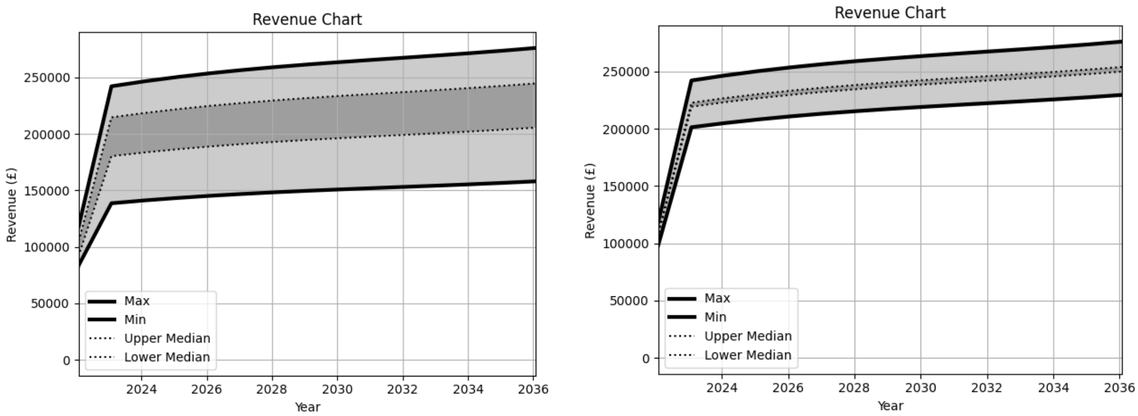

Figure S6. UK vertical farm revenue with risk and opportunities (on the left) and without risk and opportunities (on the right).

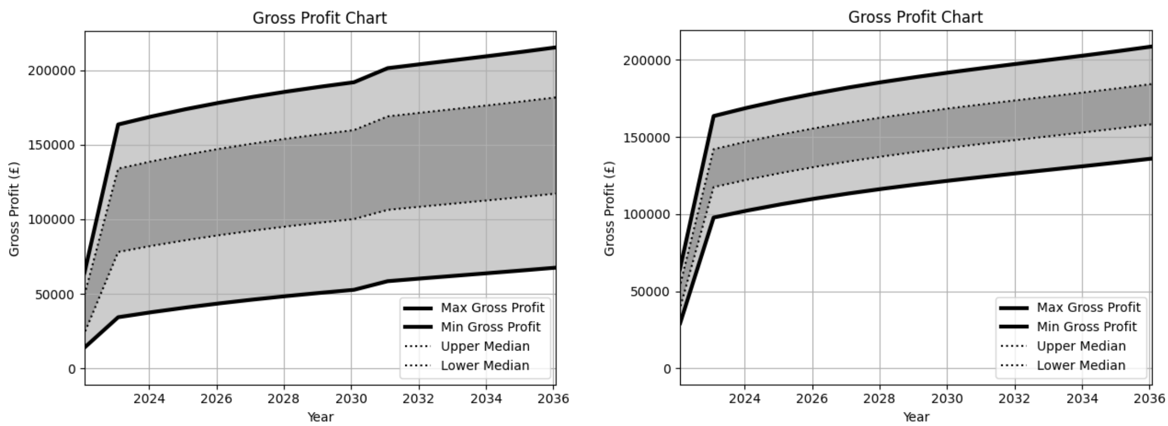

Figure S7. UK vertical farm gross profit with risk and opportunities (on the left) and without risk and opportunities (on the right).

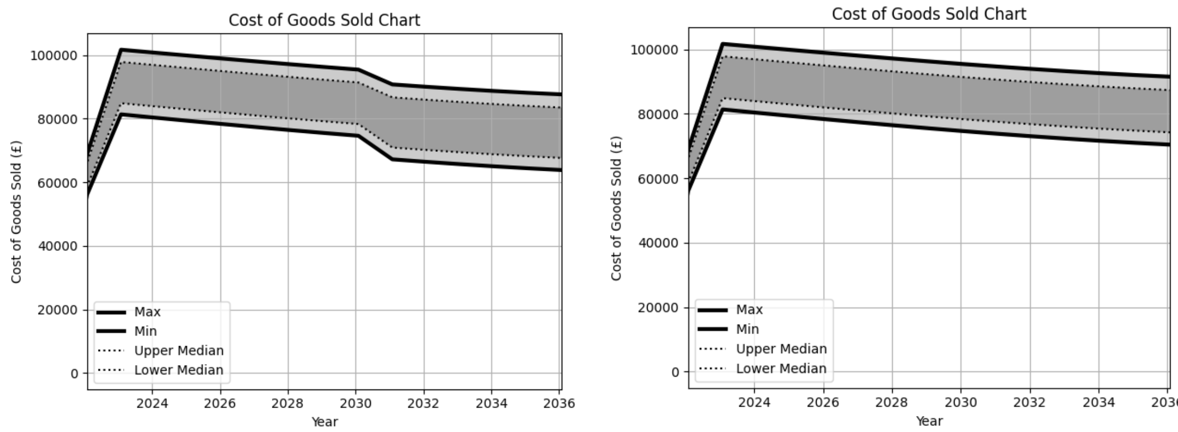

Figure S8. UK vertical farm cost of goods sold with risk and opportunities (on the left) and without risk and opportunities (on the right).

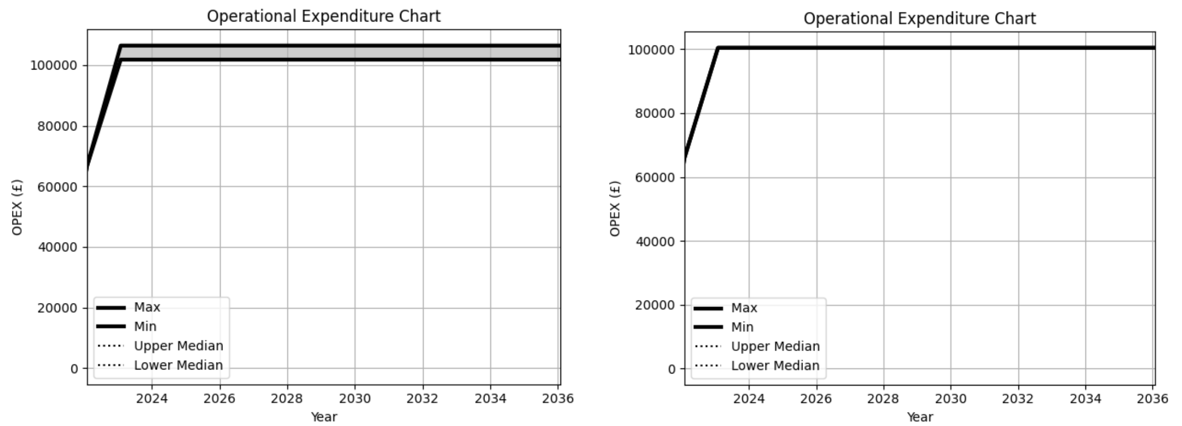

Figure S9. UK vertical farm operational expenditure with risk and opportunities (on the left) and without risk and opportunities (on the right).

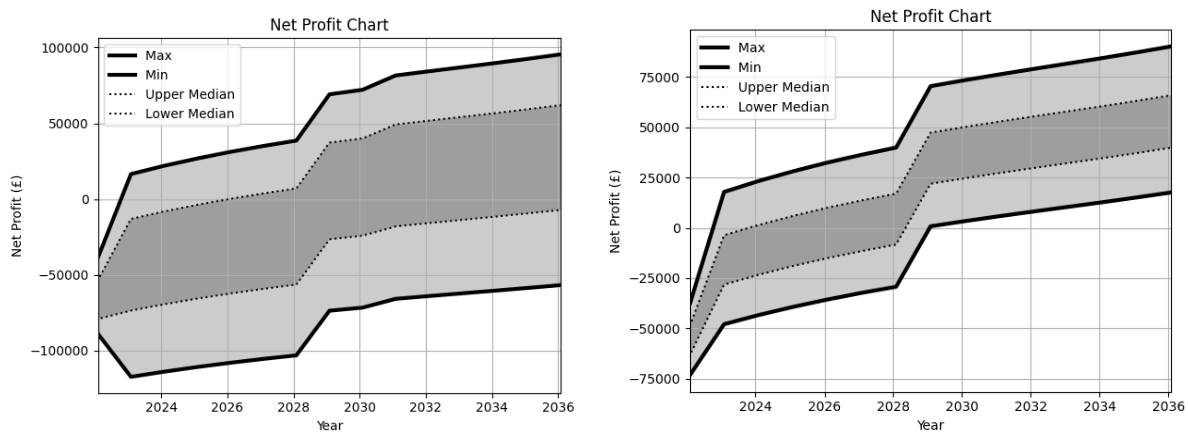

Figure S10. UK vertical farm net profit with risk and opportunities (on the left) and without risk and opportunities (on the right).

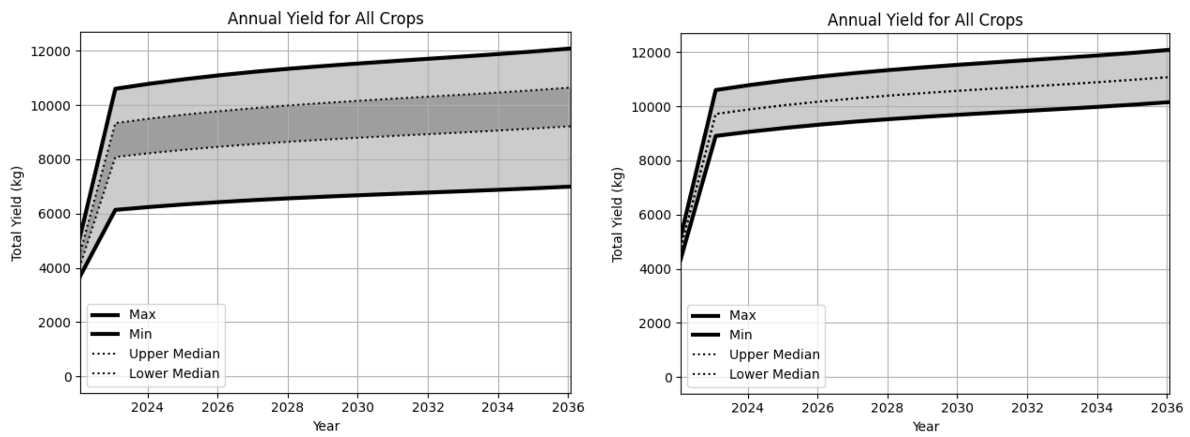

Figure S11. UK vertical farm annual yield with risk and opportunities (on the left) and without risk and opportunities (on the right).

Suggested interventions

The suggested interventions in Section 6.6.3 are manually implemented to the model (https://github.com/GaiaKnowledge/VerticalFarming) within the code (Lines 146 to 164) of 'main_pba_UK_Farm_interventions.py'. The changes made are detailed in Table S13. The results for these changes can be found in the same folder as 'results_UK_post.xlsx'.

Table S13. Interventions made to the UK farm.

Intervention	Input change	Result
Tailor nutrient solution to lettuce	Nutrient control: *medium* to *high*	Improved yield and produce quality
Provide carbon dioxide enrichment	CO_2 enrichment: *no* to *yes*	Improved yield and produce quality
Improve climate control through HVAC system	Climate control: *low* to *medium*. Additional 5-20% energy costs	Improved yield and reduced risk of pathogens and pests
Alter packaging solution with digital information	Reduce cost from £1.00 to £0.70 per unit	Reduced unit costs
Adopt robust biosecurity protocol requiring more regular cleaning of the systems	Biosecurity control: *medium* to *high*	Reduced risk of pathogen outbreaks
Use efficient distribution channels by focusing on bulk customers	Distribution unit costs are reduced by 50%	Reduced unit costs
Acquire further capital funding for proposed improvements	£100,000 grant in year 2	£20,000-30,000 additional CapEx
Utilise load shifting to optimise electricity prices [303]	From (£0.073, 0.108) to (£0.073, 0.085)	Reduced unit costs
Introduce tours of the farm with a dedicated tour guide	£2000 revenue per month (10% increase/ year) and tour guide salary budgeted	Increased revenue
Account for higher expenses	From 2% to 5% of salaries	Increased costs

associated with CO_2, nutrient solution, biosecurity and tour marketing		

These have been manually implemented as code as follows:

```
"""INPUTS CHANGED FOR AFTER INTERVENTIONS"""
scenario.capex_full += 30000
HVAC_multiplier = 1.2
sales_person.count_pilot = 1
admin.count_full = 1
scenario.climate_control = 'Medium'
scenario.nutrient_control = 'High'
scenario.co2_enrichment = 'Yes'
scenario.packaging_cost_full = 0.60
scenario.packaging_cost_pilot = 1
scenario.monthly_distribution_y2 = scenario.monthly_distribution_y1
scenario.tourism_avg_revenue_y1 = 2000
scenario.tourism_multiplier = 1.1
scenario.grants_rev_y2 += 100000 #pba.Pbox(pba.I(75000,100000))
scenario.electricity_price = minmaxmean(0.0734, 0.085, 0.079)
scenario.other_costs_full = 0.05
scenario.biosecurity_level = 'High'
```

Post-Intervention Results

Full result tables including probability bounds can be found in the model folder (https://github.com/GaiaKnowledge/VerticalFarming) as results_UK_post.xlsx. The graphs can be generated by executing the script 'main_pba_UK_Farm_interventions.py' Graphs for additional metrics not found in the main manuscript are shown in Figures S12-S20.

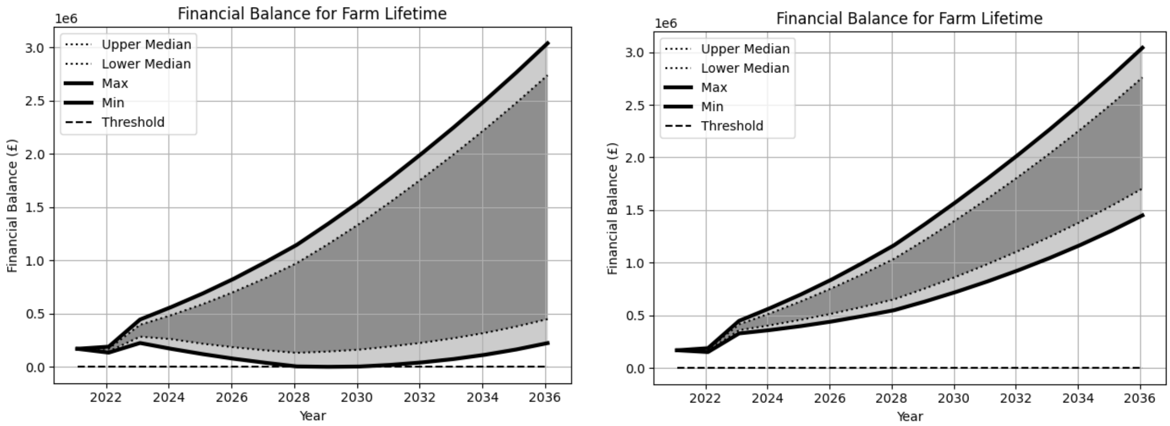

Figure S12. UK vertical farm post-intervention financial balance with risk and opportunities (on the left) and without risk and opportunities (on the right).

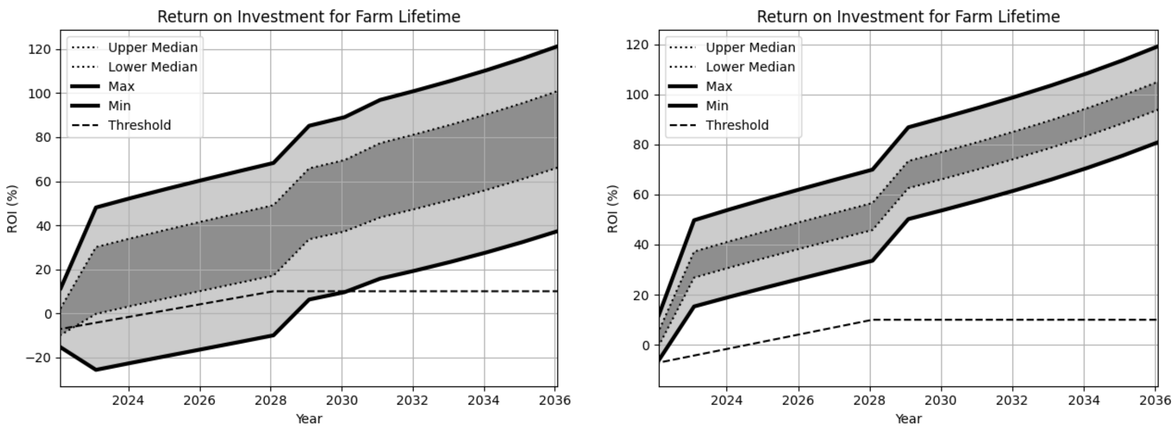

Figure S13. UK vertical farm post-intervention return on investment with risk and opportunities (on the left) and without risk and opportunities (on the right).

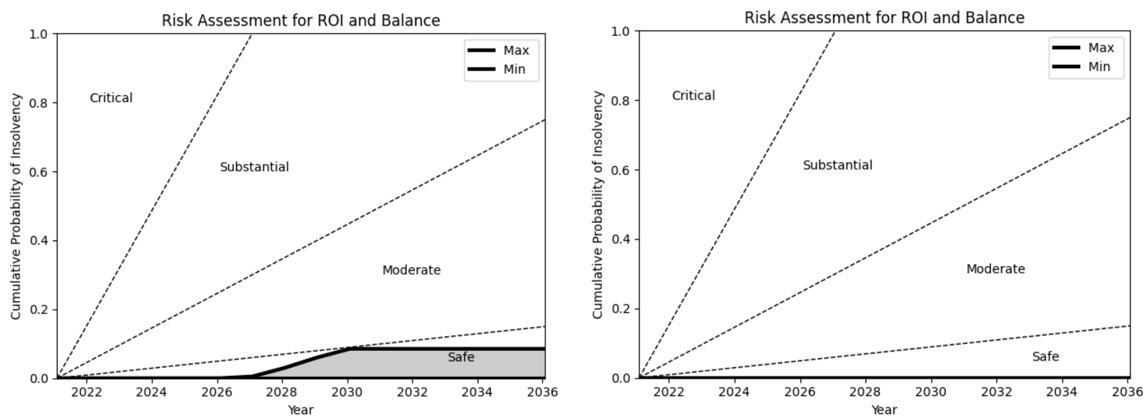

Figure S14. UK vertical farm post-intervention risk assessment with risk and opportunities (on the left) and without risk and opportunities (on the right).

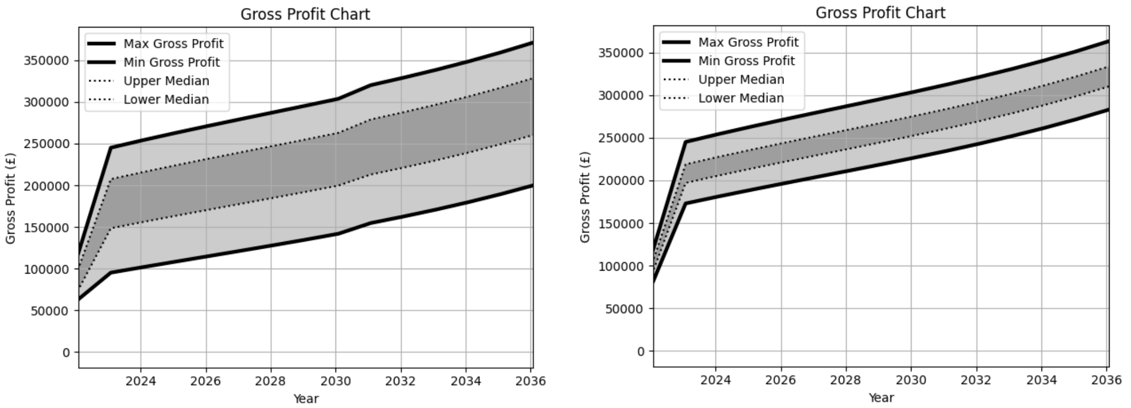

Figure S15. UK vertical farm post-intervention gross profit with risk and opportunities (on the left) and without risk and opportunities (on the right).

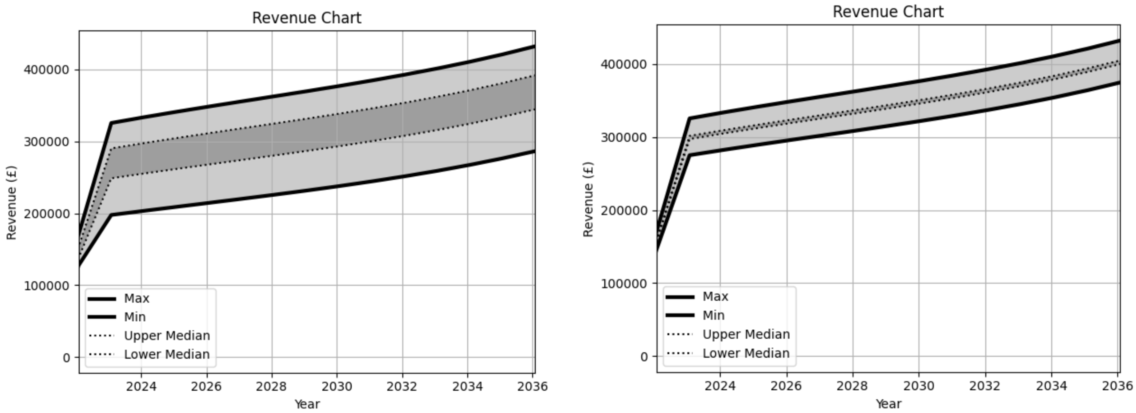

Figure S16. UK vertical farm post-intervention revenue with risk and opportunities (on the left) and without risk and opportunities (on the right).

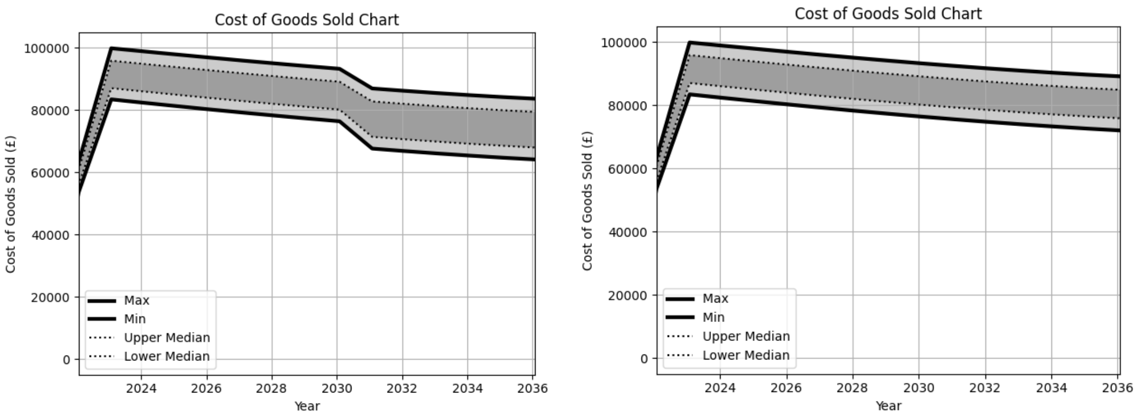

Figure S17. UK vertical farm post-intervention cost of goods sold with risk and opportunities (on the left) and without risk and opportunities (on the right).

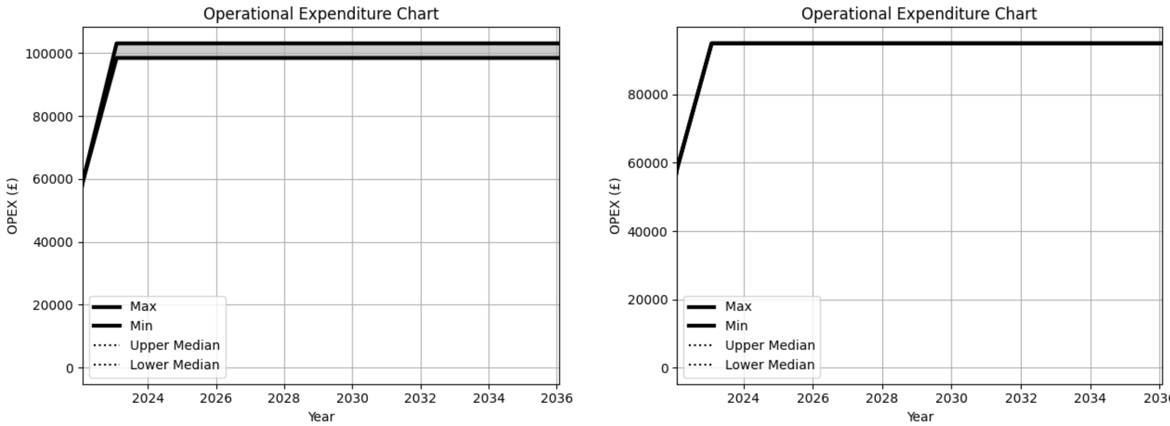

Figure S18. UK vertical farm post-intervention operational expenditure with risk and opportunities (on the left) and without risk and opportunities (on the right).

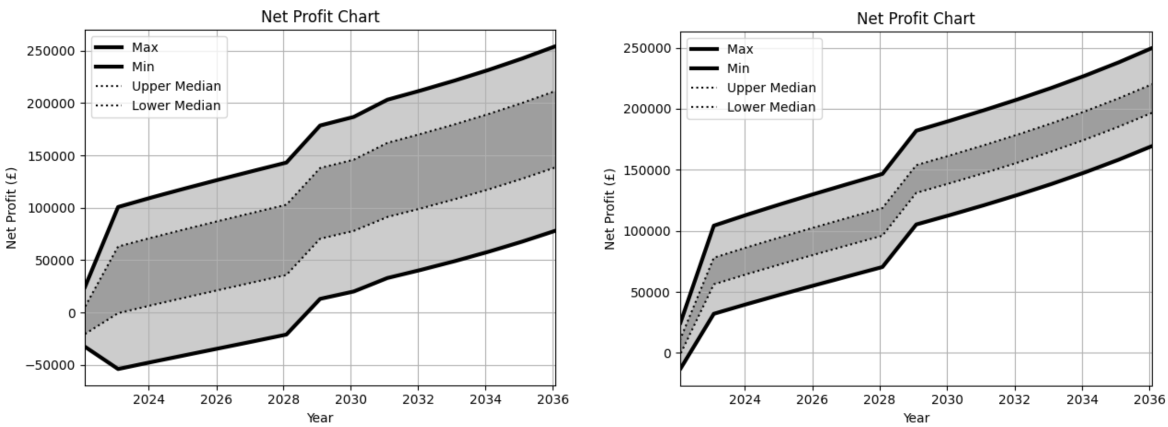

Figure S19. UK vertical farm post-intervention net profit with risk and opportunities (on the left) and without risk and opportunities (on the right).

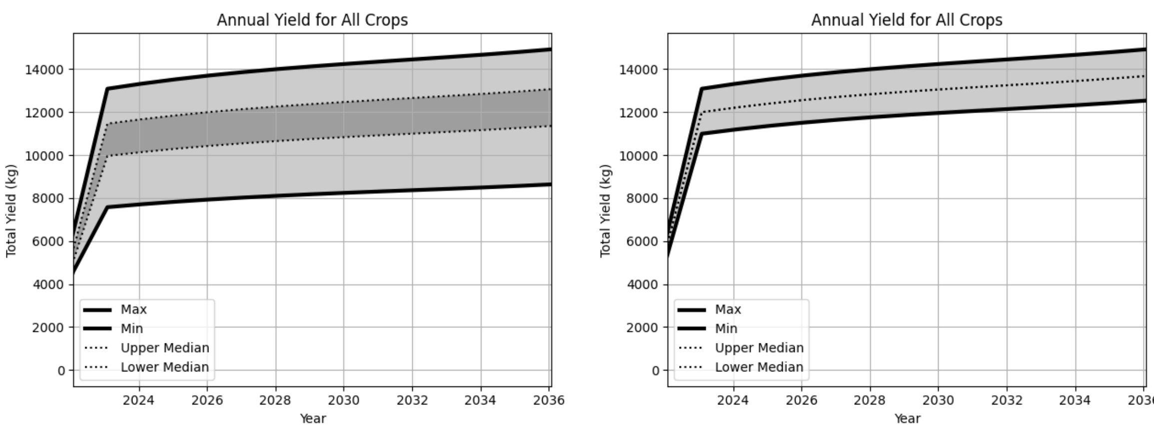

Figure S20. UK vertical farm post-intervention annual yield with risk and opportunities (on the left) and without risk and opportunities (on the right).

C.2 JAPANESE CASE STUDY

The Japanese case study data is contained within a spreadsheet called 'Current_Financial_Model_JP_PFAL.xlsx' which it executed by the model script: main_pba_JP_PFAL.py. The inputs are based on the case study provided in full within the book chapter, Smart Plant Factory, Chapter 6 [86]. Values have been converted at a rate of 1 USD = 0.72 GBP (at the time of analysis) . The farm only runs at full-production without a pilot farm included. The farm details are summarised within the tables of this section.

Farm characteristics

Japanese Farm characteristics are detailed in Table S14.

Table S14. Farm characteristics for Japanese case study (adapted with permission from [86]).

Characteristic	Japanese Hypothetical Farm	Unit
Real Estate		
Facility size	1000	m^2
Facility height	3.5	m
Space utilisation	36.4	%
Growing space	364	m^2
Systems		
Grow levels	6 shelves	
Number. of racks	241	
Stacked growing area	2184	m^2
Number of lights	5784	
Light wattage	32	W
Energy price	0.090-0.100	£/kWh
Annual electrical consumption	1,676,052	kWh
Labour		
Number of direct labourers	9	people
Number of indirect staff	5	people
Direct labour hours per week	42	hours per person
Direct hourly cost	7.34	£/hour
Crop: Lettuce		
Annual yield	116,640	kg/year
Harvest weight	0.09	kg
Photoperiod	16	hours
Product weight	1	kg
Customer segmentation	100	% to customers
Unit prices	8.64	£/unit
Packaging cost	0.05	£/unit
Attributes*		
Business model	Wholesale	
Grower experience	High	
Automation level	Medium	
Climate control level	High	
Lighting control level	High	
Nutrient control level	High	

CO_2 enrichment	Yes
Biosecurity level	High

Capital costs

The capital costs for production are detailed in Table S15. Costs are reflective of Table 6.5 in the manuscript.

Table S15. Japanese farm capital costs (adapted with permission from [86]).

Capital costs	Japanese Hypothetical Farm	Unit
Construction		
Finishing	114,775	£
Appliance	108,000	£
Management costs	0	£
Electrical infrastructure	25,200	£
Real estate	0	£
Total construction costs	247,975	£
Systems		
Growing system cost	747,072	£
Lighting system cost	538,804	£
HVAC system cost	56,160	£
Miscellaneous cost	0	
Total equipment cost	1,342,037	£
Total capital costs	1,590,012	£

Operational characteristics and costs

The operational characteristics and costs are detailed in Table S16. These values are reflective of Table 6.6 in the main manuscript.

Table S16. Operational characteristics and costs (adapted with permission from [86]).

Production costs	Japanese Hypothetical Farm	Unit
Operational expenditure		
Rent	69,120	£/year
Staff costs (non-direct labour)	171,888*	£/year
Distribution	106,691	£/year
Other costs*	8,594*	£/year
Total OpEx	356293	£/year
Cost of goods sold		
Direct labour costs	142,689	£/year
Growing media	14,818	£/year
Seeds and nutrients		
Packaging	2905	£/year
Total electricity cost	150,844	£/year
Water cost	N/A	£/year
Total COGS	375,192	£/year
Other costs		
Depreciation	162,454*	£/year

Working capital	2,160,000	£
Loan amount	0	£
Loan tenure	0	years
Loan interest	0	% per year

Model inputs

The inputs to the model are detailed in Table S17 and can be found within the model library as "Current_Financial_Model_JP_PFAL.xlsx" on the inputs sheet. As the spreadsheet does not propogate uncertainty until processed by main_pba_JP_PFAL.py, several lines of code manually input uncertainty:

```
scenario.electricity_price = pba.Pbox(pba.I(0.09,0.1))
nutrients_cost = [0, 39815, 39815, 39815, 39815, 39815, 39815, 39815, 39815, 39815,
39815, 39815, 39815, 39815, 39815, 39815]
HVAC_multiplier= 1
light_improvement = minmaxmean(0.5, 0.8, 0.65)
```

Table S17. Model inputs for Japan PFAL (adapted with permission from [86]).

#	Code	Input	Unit
1	start_date	01/02/2021	Date
2	facility_size_pilot	1000	currency
3	percent_production_area_pilot	0.364	m^2
4	growing_levels_pilot	6	%
5	weight_unit	kg	%
6	growing_area_mulitplier	1	# of levels
7	no_lights_pilot	5784	Weight unit
8	packaging_cost_pilot	£0.05	Multiplier
9	packaging_cost_full	£0.05	# of lights
10	other_costs_pilot	5.0%	£
11	farm_type	Plant Factory	£
12	business_model	Wholesale	%
13	grower_exp	High	-
14	automation_level	Medium	-
15	climate_control	High	-
16	lighting_control	High	-
17	nutrient_control	High	-
18	system_type	Bespoke (add your own)	-
19	system_quantity	241	-
20	light_system	Japanese Case Study	-
21	growing_media	Sponge	# of racks
22	ceiling_height	3.5	-
23	insulation_level	High	-
24	roof_type	Flat roof	Metres
25	co2_enrichment	Yes	-

26	structure_type	N/A	-
27	water_price	£0.000	-
28	electricity_price	£0.09	-
29	labour_improvement	5%	£
30	percentage_renewable_energy	0%	£
31	biosecurity_level	High	%/year
32	loan_amount	£2,160,000.00	%
33	tax_rate	0%	-
34	loan_interest	0%	£
35	loan_tenure	0	%
36	loan_type	Standard	%
37	crop_typ1	Lettuce - heads	Years
38	crop1_percent	100%	Type
39	crop1_system	NFT	Crop type
40	crop1_harvest_weight	0.09	% of system space
41	crop1_product_weight	1	System type
42	crop1_customer_percent	100%	Kg
43	crop1_price1	£8.72	Kg
44	crop1_price2	£0.00	%
45	crop_typ2	Basil - Lemon	£
46	crop2_percent	0.0%	£
47	crop2_system	Drip Tower	Crop type
48	crop2_harvest_weight	0.075	% of system space
49	crop2_product_weight	0.075	System type
50	crop2_customer_percent	100%	Kg
51	crop2_price1	£1.50	Kg
52	crop2_price2	£0.00	% of system space
53	crop_typ3	Basil - Genovese	£
54	crop3_percent	0.0%	£
55	crop3_system	Drip Tower	Crop type
56	crop3_harvest_weight	0.075	%
57	crop3_product_weight	0.075	System type
58	crop3_customer_percent	100%	Kg
59	crop3_price1	£1.50	Kg
60	crop3_price2	£0.00	%
61	crop_typ4	None	£
62	crop4_percent	0%	£
63	crop4_system	NFT	Crop type
64	crop4_harvest_weight	0.5	% of system space
65	crop4_product_weight	0.5	System type
66	crop4_customer_percent	0	kg
67	crop4_price1	£7.50	kg
68	crop4_price2	£7.50	%
69	vadded_products_multiplier	1	£
70	education_multiplier	1.1	£
71	tourism_multiplier	1.15	Multiplier per year
72	hospitality_multiplier	1	Multiplier per year
73	vadded_avg_revenue_y1	£-	Multiplier per year

74	education_avg_revenue_y1	£-	Multiplier per year
75	tourism_avg_revenue_y1	£-	£/month
76	hospitality_avg_revenue_y1	£-	£/month
77	monthly_rent_y1	£5,760.00	£/month
78	monthly_distribution_y1	£8,891	£/month
79	monthly_rent_y2	5760	£/month
80	monthly_distribution_y2	8890.9184	£/month
81	delivery_msalary	£1,500.00	£/month
82	farmhand_msalary	£1,500.00	£/month
83	parttime_wage	£7.34	£/month
84	ceo_msalary	£ 2,600.00	£/month
85	hgrower_msalary	£2,200.00	£/month
86	marketer_msalary	£1,800.00	£/month
87	scientist_msalary	£2,000.00	£/month
88	salesperson_msalary	£1,560.00	£/month
89	manager_msalary	£2,200.00	£/month
90	admin_msalary	£624.00	£/month
91	ceo_count_y1	1	£/month
92	hgrower_count_y1	1	£/month
93	marketer_count_y1	1	People
94	scientist_count_y1	1	People
95	salesperson_count_y1	0	People
96	manager_count_y1	0	People
97	delivery_count_y1	0	People
98	farmhand_count_y1	0	People
99	admin_count_y1	1	People
100	parttime_count_y1	1620	Hours
101	ceo_count_y2	1	People
102	hgrower_count_y2	1	People
103	marketer_count_y2	1	People
104	scientist_count_y2	1	People
105	salesperson_count_y2	0	People
106	manager_count_y2	0	People
107	delivery_count_y2	0	People
108	farmhand_count_y2	0	People
109	admin_count_y2	1	People
110	parttime_count_y2	1620	Hours
111	insurance_pilot	0	People
112	insurance_full	£0	People
113	capex_pilot	£1,590,012.00	People
114	capex_full	£1,590,012.00	£
115	capex_lights	£538,804.00	£
116	capex_facilities	£803,233.00	£
117	capex_building	£247,975.00	£
118	target_productivity_space	90	kg/m^2
119	target_productivity_energy	0.07	kg/kWh
120	target_productivity_labour	6	kg/man-hour
121	target_productivity_water	0.5	kg/L

122	target_productivity_nutrients	500	kg/kg
123	target_productivity_volume	130	kg/m^3
124	target_productivity_plants	800	No. of plants per m^2
125	target_productivity_CO2_emit	500	kg/kg
126	target_productivity_CO2_miti	50000	kg/kg
127	target_productivity_CO2_net	-1000	kg/kg
128	ipm	No	Yes/No
129	pest_detection	No	Yes/No
130	electrical_backup	No	Yes/No
131	currency	GBP	Currency
132	percent_production_area_full	36	%
133	energy_type	Average UK energy mix	-
134	grants_rev_y0	0	£
135	grants_rev_y1	0	£
136	grants_rev_y2	0	£
137	grants_rev_y3	0	£
138	grants_rev_y4	0	£
139	grants_rev_y5	0	£
140	grants_rev_y6	0	£
141	grants_rev_y7	0	£
142	grants_rev_y8	0	£
143	grants_rev_y9	0	£
144	grants_rev_y10	0	£
145	grants_rev_y11	0	£
146	daily_energy_consumption	1630	kWh
147	other_costs_full	0.03	kWh

Results

Full result tables including probability bounds can be found in the model folder (https://github.com/GaiaKnowledge/VerticalFarming) as results_JPFA.xlsx Results are visualised graphically in Figures S21-S29. The graphs can be generated by executing the script 'main_pba_JP_PFAL.py' Graphs for additional metrics not found in the main manuscript are also shown in Figures S21-S29.

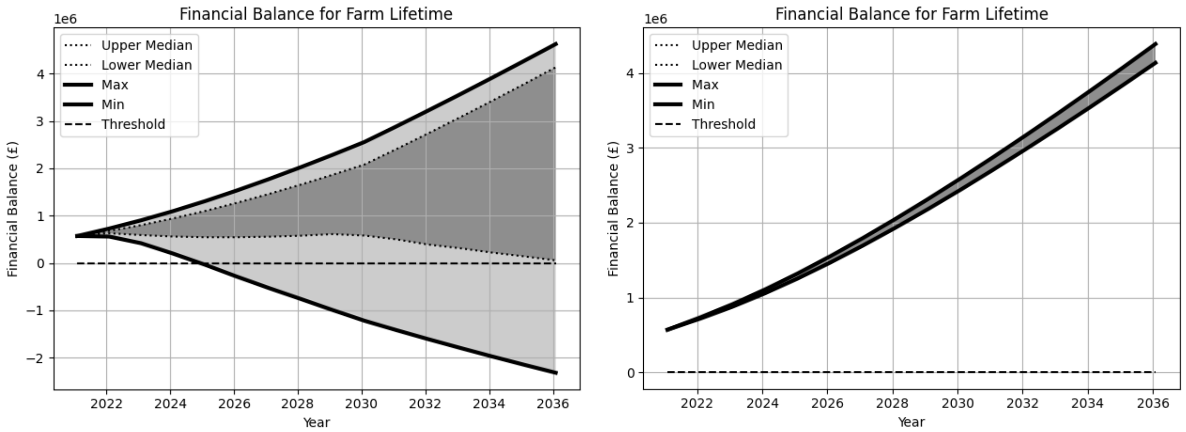

Figure S21. Japan PFAL financial balance with risk and opportunities (on the left) and without risk and opportunities (on the right).

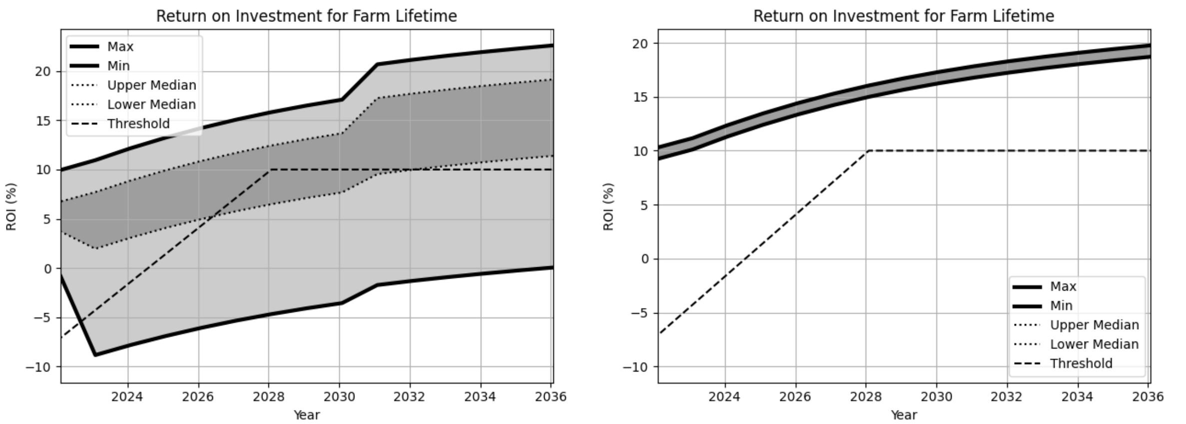

Figure S22. Japan PFAL return on investment with risk and opportunities (on the left) and without risk and opportunities (on the right).

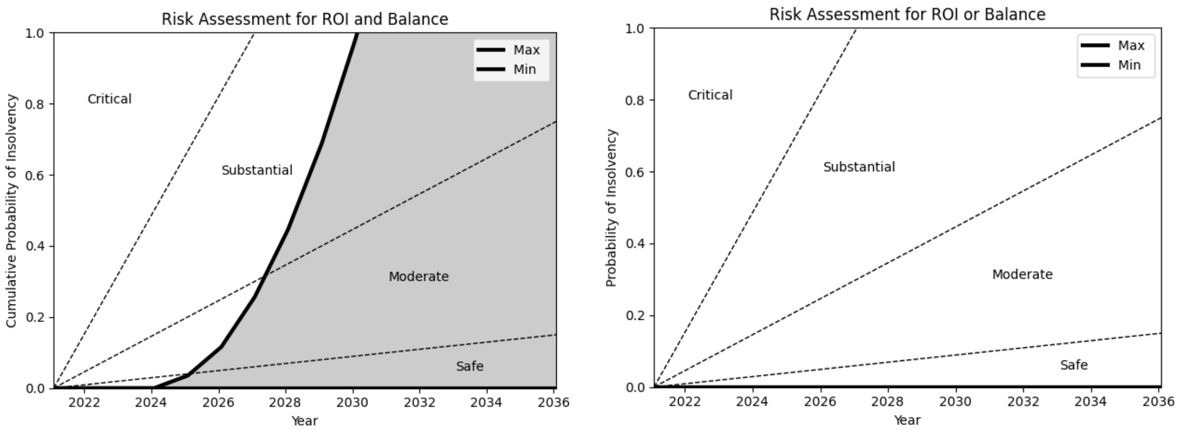

Figure S23. Japan PFAL risk profile with risk and opportunities (on the left) and without risk and opportunities (on the right).

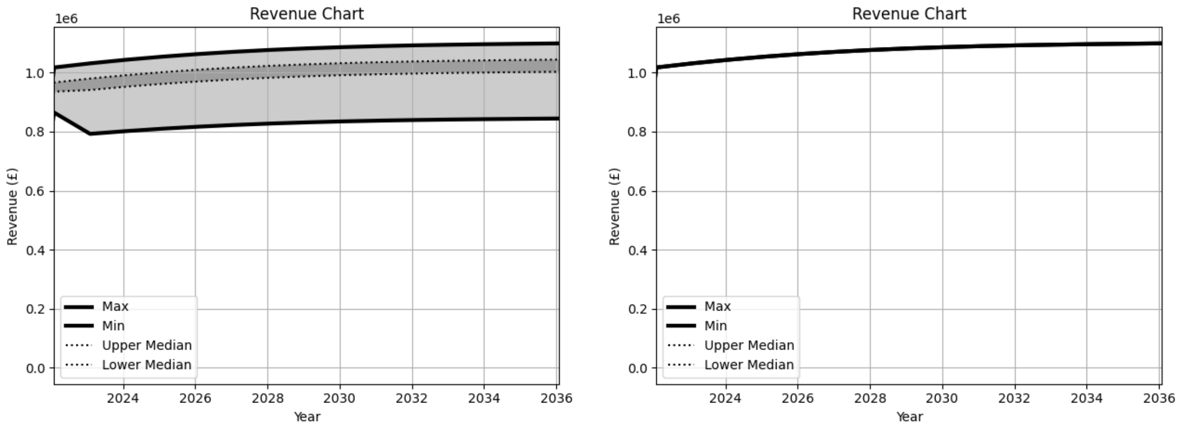

Figure S24. Japan PFAL revenue with risk and opportunities (on the left) and without risk and opportunities (on the right).

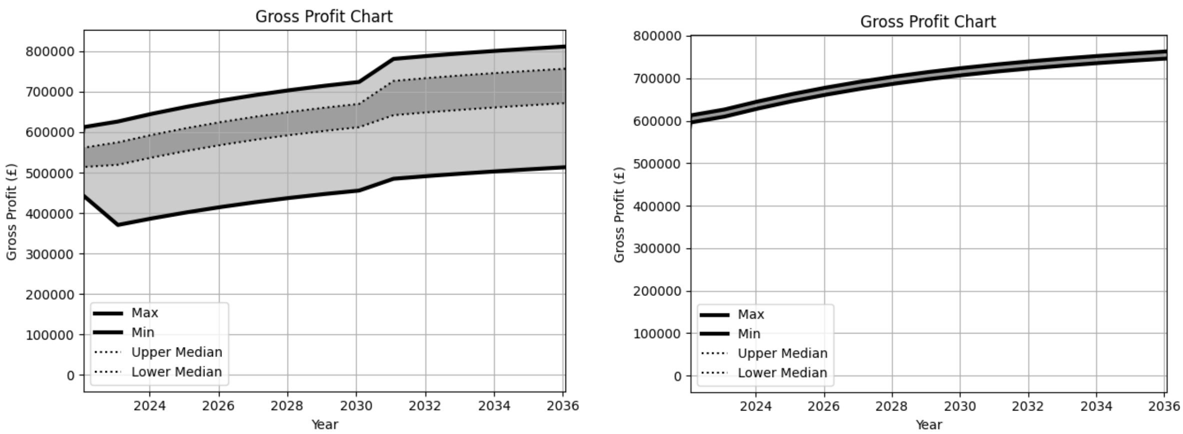

Figure S25. Japan PFAL gross profit with risk and opportunities (on the left) and without risk and opportunities (on the right).

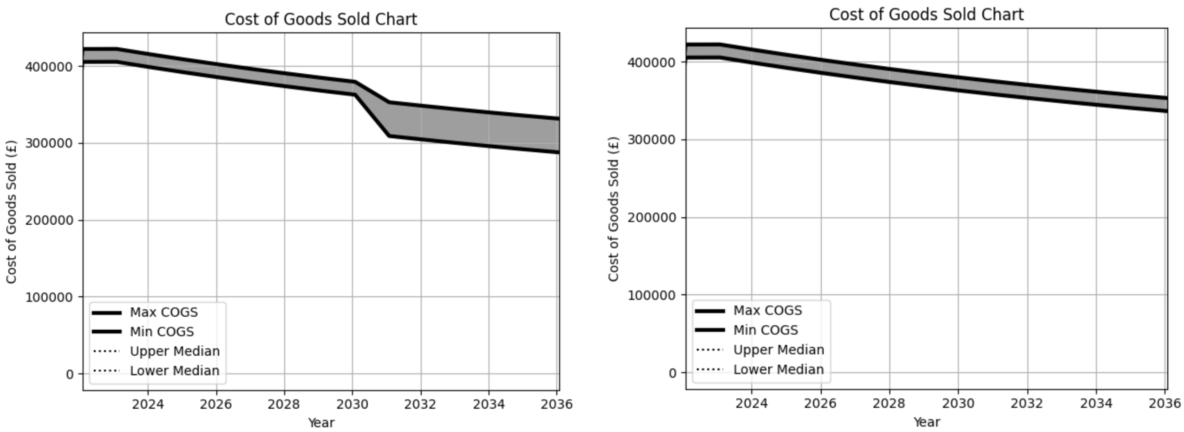

Figure S26. Japan PFAL cost of goods sold with risk and opportunities (on the left) and without risk and opportunities (on the right).

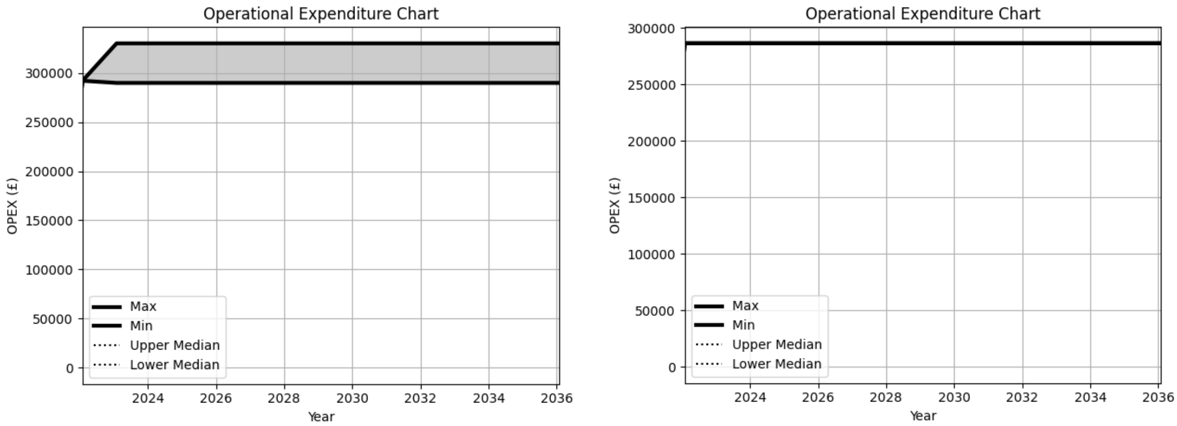

Figure S27. Japan PFAL operational expenditure with risk and opportunities (on the left) and without risk and opportunities (on the right).

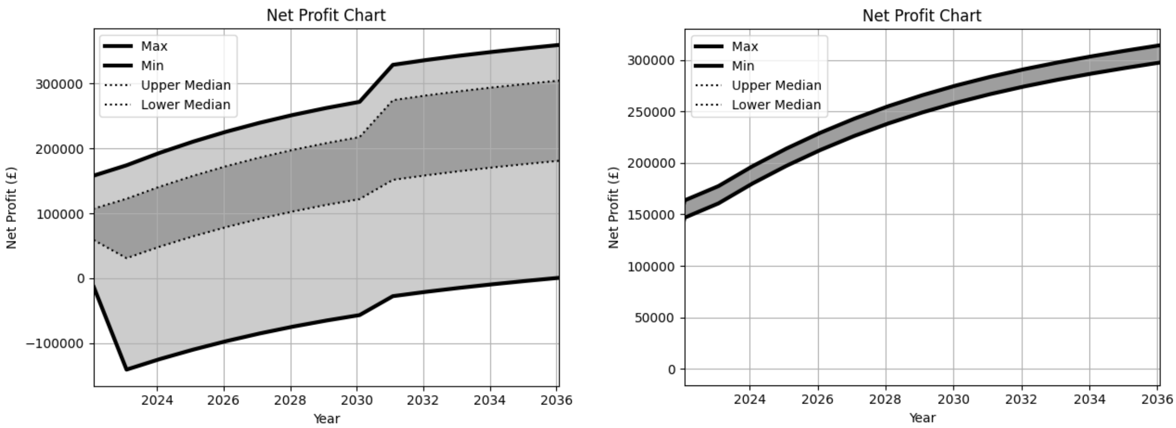

Figure S28. Japan PFAL net profit with risk and opportunities (on the left) and without risk and opportunities (on the right).

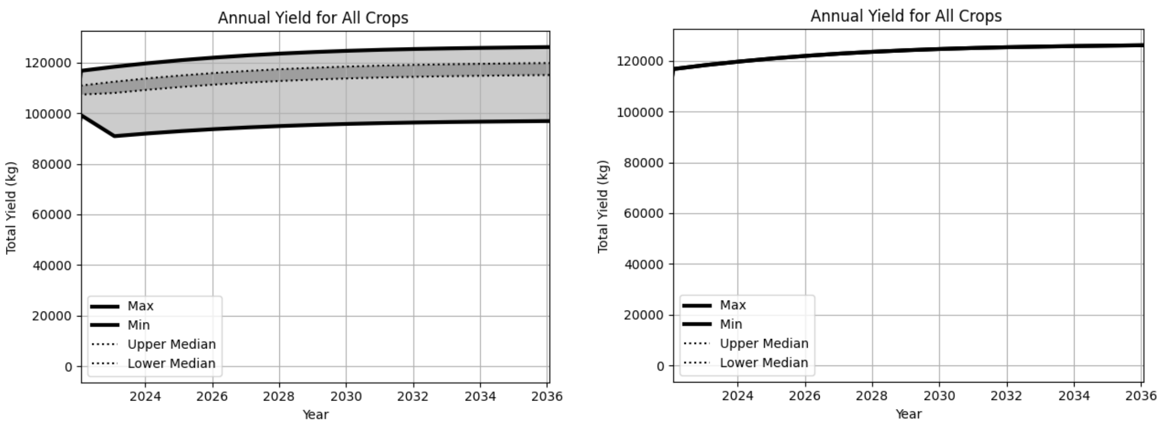

Figure S29. Japan PFAL annual yield with risk and opportunities (on the left) and without risk and opportunities (on the right).

D. Environmental Impact Model Supplementary Data

The environmental impact model (Chapter 7) that was used to compare the carbon footprint of field-based farming and vertical farming using life cycle analysis had underlying data and assumptions. In this section, the model assumptions and inputs are presented alongside their sources. The experimental design and results are also presented.

D.1 Model Assumptions, Inputs and Results

The assumptions used to develop the life cycle model for the carbon footprint comparison of field-based farming and the vertical farm case study on an annualised basis are described in Table S18.

Table S18. Assumptions for Life cycle inventory model for field-based and vertical farming scenario.

Element	Field-based agriculture	Vertical farming
Yield	Produces 3.9 kg of lettuce per m^2 per year [50].	Data collected from experiment case study
Seeds	Considered equivalent, so omitted from comparison	
Fertiliser and Nutrients	84 kg per ha cultivating lettuce in Spain [428]	Data collected from experiment case study. kg of fertiliser converted to kg of nitrogen content based on label of nutrient solution.
Growing media	Assume seeds propagated directly into soil	1.32 kg CO_2-eq per kg of rockwool [341]
Pesticides	5.24 kg of pesticides per hectare [460].	No pesticides are applied.
Fuel	Utilises tractors and machinery which consume 18-30 l (24 median) litres of fuel per hectare [461]. Average number of application rounds from tractor: 3.6	No fuel is necessary.
Water	Consumes 250 litres per kilogram of produce per year [50].	Data collected from experiment case study.
Energy	Consumes 1,100 kJ/kg of produce per year [50]. Equivalent to 0.306 kWh/kg/year. Associated emissions vary with energy type.	Data collected from experiment case study.
Waste	40% of bagged salads and lettuce is thrown away in households due to rotting and short fridge-life [462].	Assume a waste of 15% due to extended shelf-life compared with salad that has been transported (143).
Food miles	Lettuce is shipped from Spain during autumn and winter, with approximately 45 kg of CO_2-eq per 1000 kg of lettuce [463] for 1266km (assuming Madrid to London).	Lettuce is shipped from Runcorn to Liverpool (25 km), with approximately 45 kg of CO_2-eq per 1000 kg of lettuce [463].

Land	Utilises large plots of land. This reduces biodiversity through deforestation and removes plants that can sequester substantial carbon [425]	Utilises a small land footprint with a negligible effect on biodiversity as it is isolated from the natural environment.

The origin, quality and type of the data used in the model are detailed in Table S19.

Table S19. Origin, quality and type of data used

Phases	Process	Type	Source of data
Land	Field-based footprint	LD	[50]
	Vertical farm footprint	ED	Data from Heath Park case study
Nursery production	Seeds	ED, EV	Field-based: seeds reverse calculated from average weight of lettuce head. VF: data from Heath Park case study.
	Growing media use	ED, LD	Data from Heath Park case study supplemented by vendors data [464]
Cultivation operations	Water consumption	LD, ED	Field-based: [50] VF: data from Heath Park case study
	Energy consumption	LD, ED	Field-based: [50] VF: data from Heath Park case study
	Harvesting and yields	LD, ED	Field-based: [50] VF: data from Heath Park case study
Fertiliser production	Production of fertilisers	LD	[428)
	Doses of production	LD, ED.	Field-based: [428]. VF: data from Heath Park case study.
Pesticide production	Types used	SD	[460]
	Production of pesticides	LD	[465]
	Doses	SD	[460]
Agricultural machinery	Fuel-use for machinery	LD	[461]
Transport	Air-freight	LD	[463]
	Truck freight	LD	[466]
Waste	Consumer waste	LD, EV	[462]

ED: experimental raw data, SD: survey data, LD: literature data, EV: estimated values.

The resource consumption, waste, and other factors were converted into carbon dioxide and equivalent emissions (CO_2-eq). The conversion factors are detailed in Table S20.

Table S20. Carbon conversion factors for elements of life cycle inventory

Element	Carbon conversion factors	Reference
Seeds	Considered negligible and equivalent between systems so omitted.	Supplier unable to provide information.
Growing media	1.32kg of CO_2-eq per kg of rockwool plugs used.	[464]
Fertilisers	1.44kg of CO_2-eq per kg of fertiliser applied.	[429]
Pesticide manufacture	0.069 kg of CO_2-eq per MJ/t crop.	[465]
Energy	kg of CO_2-eq per kWh depends on source of energy, see Table S21.	[467]
Water	0.149 kg of CO_2-eq per litre of water.	[467]
Fuel	2.5 kg CO_2-eq per litre of diesel.	[467]
Food miles	45kg per 1000kg of lettuce through air-freight travel.	[463]
Waste	1.15 kg of CO_2-eq per kg of European produced lettuce. For an indoor farm, CO_2-eq is the summation of associated emissions of wasted produce.	[465]
Land-use	kg of CO_2-eq per square-metre of land deforested depends on natural biome of area in Table S22.	[425]

The energy consumption was converted to carbon emissions depending on the source of energy production. Sources and their values for conversion were scattered and disparate, therefore the mid-range was used as an approximation for the model. In 2014, the Intergovernmental Panel on Climate Change examined energy systems and collated existing literature to provide many of the estimates used in this study [468]. Table S21 details the conversion values from energy source to gCO2-eq per kWh estimated from the mid-range with the associated reference.

Table S21. Estimated emissions per kWh produced from various types of power plants [431,468–471].

	Energy Source	**Emissions of gCO_2-eq per kwh**		**Reference**
		Range/Value	Mid-range	

Electricity output g/kWh$_{out}$	UK grid average	233	233	[467]
	Spanish grid average	167	167	[472]
	Hard coal	710-950	830	AR5 [431,468]
	CCS Coal	70-290	180	AR5 [468]
	Natural gas	410-650	530	AR5 [468]
	Oil	510-1170	840	SRREN [468]
	Nuclear	0-100	50	AR5 [468]
	Biomass (Biopower)	8.5-130	-112.5	SRREN [468]
	Hydropower	0-2200	1100	AR5 [431]
	Solar energy	10-60	35	AR5 [468]
	Solar photovoltaic	30-140	85	AR5 [468]
	Wind	20-70	45	AR5 [468]
	Geothermal	10-60	35	AR5 [468]
	Ocean/tide energy	12-25	20	AR5 [468]
	Hydrogen SMR	280	280	[471]
	Green Hydrogen	25-178	131	[469,470]
	Blue Hydrogen	23-150	86.5	[470]

The environmental impact model considers deforestation and sequestration of carbon of natural biomes to consider the wider view of carbon emissions. Table S22 presents the carbon sequestration rates recorded in the literature.

Table S22. Average carbon sequestration rates for natural biomes per acre (cf. [427,432]).

Biome	**Crop land**	**Grasslands**	**Wetlands**	**Deserts**	**Boreal forests**	**Temperate forests**
kg CO_2 sequestered per acre per annum	33,566	97,976	186,880	18,144	165,108	61,689

The characteristics for the two case studies examined are shown in Table S23

Table S23. Characteristics of a hypothetical field-based farm and experimental vertical farm analysed.

Production System	Field-based	Vertical farm
Production land area (m^2)	10,000	3.3
Non-productive land area (m^2)	Negligible	3.3
Total land area (m^2)	10,000	6.6
Crop frequency analysed	1 harvest (Autumn)	One crop cycle (50 days)
Number of systems	N/A	Two racks of eight 5-ft towers, extrapolated to 8-ft towers.
Production yield per annum (kg)	39,000	154
Location of farm	Murcia, Spain	Runcorn, United Kingdom
Distance from North West, UK, km	1700	0

The results of the life cycle analysis on the two case studies are shown in Table S24 for an annualised basis.

Table S24. Results for field-based farm and vertical farm from cradle-to-grave alongside associated GHG emissions (Blue Hydrogen for Vertical farm, Spanish grid electricity for conventional)

Phase	Field-based			Vertical farm		
	Unit	kg of CO_2-eq	kg of CO_2-eq per kg of produce	Unit	kg of CO_2-eq	kg of CO_2-eq per kg of produce
Yield	39,000kg	N/A		154.0 kg	N/A	
Cradle:						
Land (deforestation)	10,000 m^2	152,400	3.908	6.6 m^2	100.6	0.6535
Embedded carbon in equipment	-	-	-	-	-	-
Fertilisers/Nutrients	84 kg	121.0	0.00310	1.28 kg	1.840	0.0119
Seeds	239,264 seeds	-	-	1,426 seeds	-	-
Growing media	0 plugs	0	0	1426 plugs		0.0156
Cultivation process (inc. propagation):						
Water consumption	9,750,000	3,350	0.0860	3080	1.059	0.0069

	L			L		
Energy consumption	11,900 kWh	1561	0.0510	5800 kWh	133.5-870.3 Mid-range: 501.9	0.87-5.65 Mid-range: 3.26
Pesticide usage	5.237kg	403.7	0.0104	0 kg	0	0
Petrol for farm machinery	86.36 L	216	0.0055	0 L	0	0
Distribution:						
Food miles	2,400km	20,310	0.5208	25km	0.8353	0.0054
Consumer (Grave):						
Waste	15,600 kg	17,940	0.4600	23.09 kg	88.2	0.573
Totals						
Total kg of CO_2-eq	197,000			684		
kg of CO_2-eq per kg of lettuce (inc. deforestation)	5.05			4.45		
kg of CO_2-eq per kg of lettuce (exc. deforestation)	1.14			3.81		

The sensitivity analysis conducted showed the amount of carbon emissions for the vertical farm were highly sensitive to energy type and a deeper examination of the results for various energy types is detailed in Table S25.

Table S25. CO_2 emissions for the energy component of a vertical farm dependent on different energy sources

Energy Source	Emissions factor (gCO_2-eq/kWh)	Energy associated carbon footprint (mid-range value) kg of CO_2-eq per kg of lettuce	Reduction in energy-based carbon footprint (compared to UK grid)
UK Main grid	233	8.79	-
Wind energy	45.0	1.70	7.09
Blue Hydrogen fuel-cell	86.5	3.26	5.53
Solar energy	35	1.32	7.47
Ocean/tide energy	20	0.75	8.04

Nuclear energy	50	1.88	6.91
Geothermal	35	1.32	7.47
Coal CCS	180	6.78	2.01

D.2 VERTICAL FARMING CASE STUDY

Experimental Design

One experiment was conducted at the Heath Business Park in Runcorn, UK (Lat: 53.3248419, Long: -2.7356285), using two experimental units. Each experimental unit consisted of 8, 5-foot Zipgrow [187] hydroponic grow towers, equipped with an 80 litre sump, and with water recirculated using a Jecod Marine DCP-2500 pump through a TMC Vectorn 120 UV Aquarium Steriliser. Eight GE Arize LED lights (GEHL48HPKB1, 31.8W) provided illumination and each system had a Bluelab Pro Controller and M3 Peripod for nutrient dosing and pH and EC control, and monitoring. The systems were situated in a room of dimensions 328 × 199 × 262 cm (length × width × height), with ventilation provided by two Toolzy quiet 6-inch inline 50 W controllable duct fans.

Electrical power use of the individual systems were monitored using Sonoff POW R2 wifi smart switches, flashed with the Tasomota OS, and a custom setup using a NodeMCU Lolin V3 microcontroller for monitoring power usage by the hydrogen fuel cell. Environmental conditions in the room were monitored using a custom setup using a Raspberry Pi 4, two Arduino Wifi Unos, and sensors from DFrobot (CO_2: SEN0219, temperature and humidity: SEN0137).

The nutrients provided to the plants were VitaLink Hydro MAX Grow for soft water from Hydrogarden [473], and pH control was carried out using Phosphoric Acid 85% from APC Pure [474].

The power for the experiment came from a hydrogen fuel cell provided by TCP group [475] . The fuel cell itself was a Model Eco-GH2 manufactured by Taylor Construction Plant Ltd, using a PEM Fuel Cell Intelligent Energy model S801, running at 28.8 V with a maximum output of 1000 W. The battery inverter system was a Model PP2500 from Light Green Power Ltd with a direct current (DC) operating voltage of 24 V and an AC operating voltage 240 v at 50 Hz.

Experimental Protocol

150 Multi-Leaf Butterhead Salanova Hawking lettuce from Justseed (RZ 79-135) were sown into 150 Cultilene rockwool propagator cubes (dimensions: 25 × 25 × 40 mm) that had been soaked for 15 minutes in a solution containing 1 ml per litre of A and B nutrient solution and were then placed in a 150-well tray containing 0.5 cm of tap water under a plastic cloche. The plugs were left in the dark for 36 hours before being placed under two GE Arize LED lights (GEHL48HPKB1, 31.8 W) set to a 16 hour photoperiod. The cloches were removed 4 days after sowing, upon seedling emergence. At the two-leaf growth stage at day 8, the water in the grow trays was replaced with water containing 3 ml per litre of A and B nutrient solution, which was then regularly replaced every 3-4 days. The extractor fans were initially off, but were turned on to their lowest setting, (level 1) on day 11.

128 randomly selected seedlings were transplanted into the Zipgrow towers in the main systems on day 17 after sowing, with 8 seedlings planted at regular intervals in each of the 8 towers in each system. The EC of the tap water in the system was 0.5, so the EC was initially maintained at 1.8, however, tip burn started to be observed in the leaves at day 26, whereupon the EC was lowered to 1.6. pH was maintained at a constant level of 5.8 throughout. The extractor fans were turned to setting 2 on transplanting, and to setting 4 on day 23. On day 31, the fan speed was increased to 5 and a small 40 W fan was added to the room to provide airflow directly over the plants.

The plant samples were harvested at day 50, the grow plugs were removed and the lettuce weighed and placed in paper bags for drying. 127 lettuce were harvested in total as one was removed for an unrelated analysis. The lettuce were dried for 5 days at 60°C, the dried mass was weighed and 8 randomly selected samples sent to Forest Research for foliar carbon/nitrogen (C/N) analysis.

Experimental Results

The experiment ran over 50 days and the environmental conditions were as in Table S26.

Table S26. Growing conditions during the trial

Variable	Min	Max	Mean
Air Temperature (°C)	17.6	24.4	20.9
Humidity (%)	47.7	88.3	69.0
CO_2 (ppm)	321.0	687.0	461.1

127 lettuce were produced, and their wet and dry weights were as in Table S27.

Table S27. Weights of lettuces produced during the trial

Weights	Wet (grams)	Dried (grams)
Minimum weight	31.2	1.7
Maximum weight	195.6	13.6
Average weight	108.4	5.6
Standard Deviation	30.7	2.1
Total weight	13766.80	706.60

The carbon and nitrogen analysis for the randomly selected sample of 8 lettuce was as in Table S28.

Table S28. C/N analysis for the lettuce

C/N Analysis	N%	C%
Average	5.977	37.60
Standard Deviation	0.2589	0.91

The total mass of carbon produce during the experiment was therefore, the dry weight of the lettuce multiplied by the average percentage of carbon: $706.60 \times (37.60 \div 100) = 265.68$ g.

The water and nutrient used by the system was as in Table S29.

Table S29. Water and nutrient use

System	Water (litres)	Nutrients A+B (millilitres)	Nitrogen (kg)
1	103.5	1447.8	0.069
2	91.5	1847.4	0.089

The energy used by the individual systems during the different growing stages are as in Table S30.

Table S30. Energy use during the experiment

Growing Stage	Item	Power (kWh)	kWh per day
Propagation	Lights	16.05	0.94

(17 days)	Fans	0.81	0.05
Growing (33 days)	System 1	140.89	4.27
	System 2	166.29	5.07
	Fans	23.30	0.71
Total		347.34	11.04

The power draw on the fuel cell was measured throughout the experiment, but network errors meant that there was only consistent data for the final 31 days of the experiment. Over this time, the power use of the fuel cell compared to the total use by the systems and fans was:

- Combined power use of systems: 321.06 kW
- Power use of fuel cell: 474.80 kW

This ratio of power use by the fuel to that of the systems was largely constant at 1.479. Given that the total power use by all systems during the experiment was 348.34, the expected power use by the fuel cell is: $348.34 \times 1.479 = 515.19$ kW
The total volume of hydrogen used was 477 m^3.

E. Ethical Approval for Interviews

The interview study (Chapter 4) required ethics approval for site-visits, interviews and surveys. In this section, proof is given of ethical approval acceptance for the study by the University of Liverpool (Figure S30) alongside the approved documents we prepared Figure S31.

E.1 Acceptance Letter

UNIVERSITY OF LIVERPOOL

Faculty of Science and Engineering Research Ethics Committee

17 June 2019

Dear Prof Ferson

I am pleased to inform you that your application for research ethics approval has been approved. Application details and conditions of approval can be found below. Appendix A contains a list of documents approved by the Committee.

Application Details

Reference:	4071
Project Title:	Identifying challenges and barriers to profitability for indoor farms
Principal Investigator/Supervisor:	Prof Scott Ferson
Co-Investigator(s):	Mr Francis Baumont De Oliveira, Dr Ronald Dyer
Lead Student Investigator:	-
Department:	Civil Engineering and Industrial Design
Approval Date:	17/06/2019
Approval Expiry Date:	Five years from the approval date listed above

The application was **APPROVED** subject to the following conditions:

Conditions of approval

- All serious adverse events must be reported to the Committee (ethics@liverpool.ac.uk) in accordance with the procedure for reporting adverse events.
- If you wish to extend the duration of the study beyond the research ethics approval expiry date listed above, a new application should be submitted.
- If you wish to make an amendment to the study, please create and submit an amendment form using the research ethics system.
- If the named Principal Investigator or Supervisor leaves the employment of the University during the course of this approval, the approval will lapse. Therefore it will be necessary to create and submit an amendment form within the research ethics system.
- It is the responsibility of the Principal Investigator/Supervisor to inform all the investigators of the terms of the approval.

Kind regards,

Faculty of Science and Engineering Research Ethics Committee

foseeth@liverpool.ac.uk

0151 795 0649

Figure S30. Evidence of ethical approval from University of Liverpool for interview study.

E.2 Approved Documents

Appendix - Approved Documents

(Relevant only to amendments involving changes to the study documentation)

The final document set reviewed and approved by the committee is listed below:

Document Type	File Name	Date	Version
Default	ChairApprovalEmail	13/05/2019	1
Study Proposal/Protocol	Hemming_et_al-2018-Methods_in_Ecology_and_Evolution (1)	16/05/2019	1
Participant Consent Form	V6-Consent Form-FrancisBaumontDeOliveira-Observation	16/05/2019	6
Interview Schedule	interviewv24	16/05/2019	24
Fieldwork Risk Assessment	sgfbaumo_21-05-2019_17-30-44_1	21/05/2019	1
Advertisement	Advertisement-Ethical-Approvalv9	11/06/2019	9
Participant Consent Form	V2-Consent Form-FrancisBaumontDeOliveira-Interviews_Overseas	11/06/2019	2
Participant Consent Form	V11-Consent Form-FrancisBaumontDeOliveira-Interviews_UK	11/06/2019	11
Advertisement	Advertisement-Ethical-Approvalv9	11/06/2019	9
Questionnaire	Questionnaire4	11/06/2019	4
Participant Information Sheet	Participant-information-sheet-v11_Interviews	11/06/2019	11
Participant Information Sheet	Participant-information-sheet-v3_OverseasInterviews	11/06/2019	3
Advertisement	Advertisement-Ethical-Approvalv9	11/06/2019	9
Participant Consent Form	V7-Consent Form-FrancisBaumontDeOliveira-Observation	11/06/2019	7
Participant Information Sheet	Observation-Participant-information-sheet-v12	13/06/2019	12

Figure S31. The approved documents for conducting the interview study.