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A Collaborative Decision Support System Framework for Vertical Farming Business Developments

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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.

KEYWORDS

Artificial Intelligence, Business Sustainability, Decision Support, Imprecise Data, Risk Assessment, Vertical Farming

INTRODUCTION

Background

Feeding a predicted 9.8 billion people by 2050 (UN DESA, 2017) 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% (Hunter et al., 2017). 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 (WWF, 2019), (ii) its loss and waste of an estimated 33% of all food (FAO, 2019), producing 8% of global greenhouse gas emissions (FAO, 2011), and (iii) food contamination accounting for 600 million people falling ill, 420,000 people dying and $95 billion annually in lost productivity (WHO, 2019). 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 1 delineates the concepts of UA, indoor farming and VF, and how these classifications may overlap.

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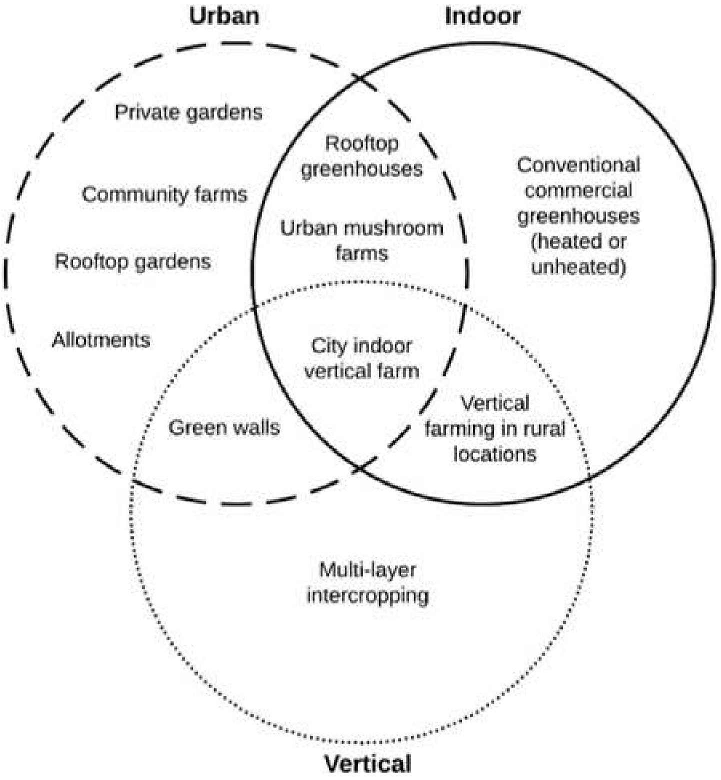
Figure 1. A Venn diagram to classify agriculture according to whether it is urban, indoor or vertical, or a combination. Adapted from (Breewood, 2019).



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 (Al-Kodmany, 2018; Baumont De Oliveira, 2020). Using CEA processes, environmental factors can be finely tuned for optimum growing conditions which are commonly called "crop growth recipes" (Meinen et al., 2018). 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 (Agrilyst, 2018; Agritecture & Autogrow, 2019; Hughes, 2018).

There are numerous benefits of VF when compared to conventional agricultural methods:

1. Minimising horizontal space requirements and increasing yield per unit area (Touliatos et al., 2016);
2. Reducing dependence on pesticides or herbicides (Marks, 2014);
3. Cutting water consumption by approximately 70%-95% (Barbosa et al., 2015; Bradley & Marulanda, 2001; Despommier, 2010);
4. Producing reliable year-round crop in soil-less environments independent of weather (Despommier, 2010);
5. Reducing the necessity for storage, transport and refrigeration by local production (Despommier, 2010);

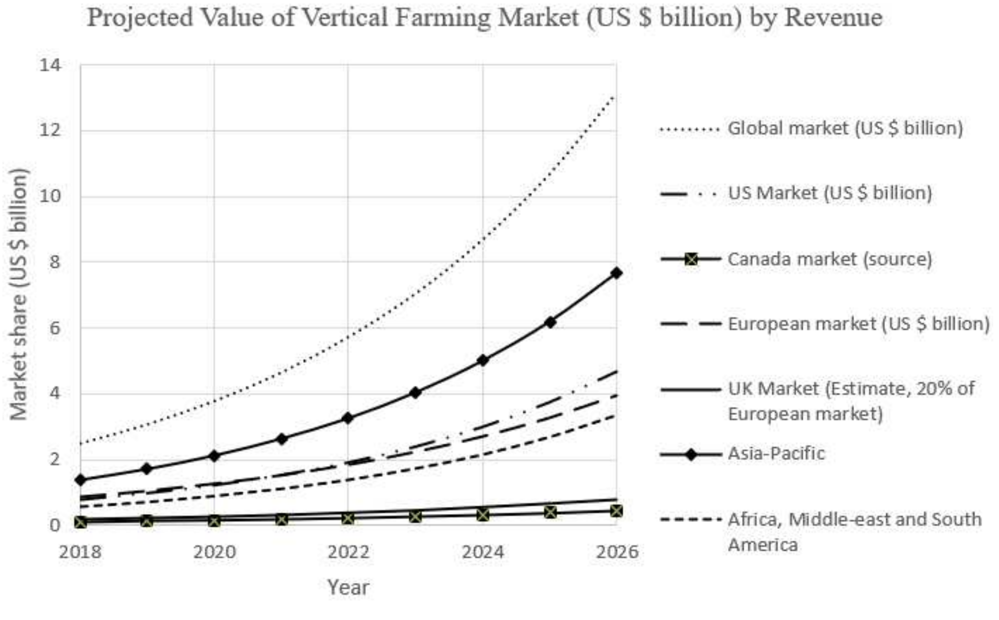
6. Increasing food safety through reduced variabilities of wildlife and increased traceability (Despommier, 2010; Gordon-Smith, 2019);
7. Reducing direct dependence on fossil fuels by operating electrically (Despommier, 2010).

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 (Benke & Tomkins, 2017; Liotta et al., 2017). Figure 2 shows the trajectory for market growth over the next 6 years based on market research reports (Allied Market Research, 2017; Arizton, 2019; Grand View Research, 2019; KBV Research, 2017a, 2017c, 2017b; Knowledge Sourcing Intelligence LLP, 2018; market.us, 2019, 2018; Market Data Forecast, 2018b, 2018a; Pulidindi & Chakraborty, 2018).

Despite an initial boom in the VF sector, the practice has struggled to be widely adopted without a trained workforce (Benke & Tomkins, 2017; Kummer, 2018; Liotta et al., 2017). 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 (Agrilyst, 2018; Kummer, 2018). Economic viability has been identified as one of the largest obstacles to realising VF projects (Shao et al., 2016), and whilst it has been reported in prominent surveys that there are existing profitable operations (Agrilyst, 2018; Agritecture & Autogrow, 2019), 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 (Sijmonsma, 2019), (ii) underestimated labour costs (Liotta et al., 2017), (iii) lack of adequate VF knowledge and accessible education (Liotta et al., 2017), (iv) inefficient workflow and inadequate ergonomic design consideration (Kummer, 2018; Liotta et al., 2017), (v) low profitability margins

Figure 2. The expected market growth for VF by revenue from aggregated values and averaged compounded annual growth rates values (see text)



(Kummer, 2018), (vi) costly equipment failures (Denis & Greer, 2018; Liotta et al., 2017) and (vii) poor early decisions around pricing, crop selection and location (Liotta et al., 2017; Michael, 2017). Preliminary results indicate about 85% of food-focused VFs fail within several years without further capital investment (Gauthier, 2018). Projects struggle to realise an acceptable return on investment (ROI) above 10% for investors (Kummer, 2018). 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. Thriving as a business that transforms agriculture is another matter." (Kummer, 2018).

Due to the risk and investment required, there is naturally some secrecy around business models and lessons learned (Kummer, 2018). Projects have received large investment rounds but in some cases insiders complain it is mostly "smoke and mirrors" (Brodwin, 2019a, 2019b), 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 (Burwood-Taylor, 2018; Kuack & UrbanAgNews.com, 2019; Kummer, 2018) and academic research is needed to support the emergence of the sector (Kozai, 2015; Shao et al., 2016). VF requires a complex "urban food-water-energy nexus" approach (JPI Urban Europe, 2018). 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 (JPI Urban Europe, 2018).

Currently, detailed financial analyses of CapEx, OpEx and revenues have been hard to produce, due to the complex nature of combining architecture and agriculture (Shao et al., 2016). Calculations tend to be for a particular scenario, and they are difficult to generalise (Shao et al., 2016). From an investment perspective, a clear plan for profitability is required (Agroecology Capital, 2019).

> *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 (Agritecture & Autogrow, 2019)*

Investors are beginning to recognise vertical farms are a long-term play and require patient capital (Gordon-Smith, 2019). 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 (Shao et al., 2016).

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 (Agritecture & Autogrow, 2019). 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 2).
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).
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 4).
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 5).

LITERATURE REVIEW

The literature review covers three 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.

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. Baumont De Oliveira (2020) 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. Shao et al. (2016) argue that researchers must collaborate with existing small-scale pioneers of vertical farming to develop and refine increasingly accurate cost models (Shao et al., 2016). A clear route to profitability is recognised by practitioners and researchers as a requisite step to enable financial investment and inform policy-makers (Banerjee & Adenaeuer, 2014; Hughes, 2018; Kummer, 2018; Shao et al., 2016). Baumont De Oliveira (2020) concludes that from all the economic analyses conducted in the literature for VF, only one attempt, “VFer” (Shao et al., 2016), 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 (Baumont De Oliveira, 2020). 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.

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 (Rose et al., 2016). For farmers and their respective advisers, DSSs can help facilitate effective farm management by making scientific knowledge and rational risk management algorithms accessible (Rossi et al., 2014). They also enable efficient recording of data which can be automatically analysed to generate empirical recommendations and alerts. (Rossi et al., 2014). Two key reviews have been conducted on agricultural DSSs: 11 years ago on 70 crop protection DSSs in Europe (Been et al., 2009) and 15 years ago on a taxonomy of all 624 DSSs in published works at the time (Manos et al., 2004). 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 (Been et al., 2009). 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.

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 (Gent et al., 2011; Matthews et al., 2005; Rossi et al., 2014). This has been labelled the "problem of implementation" (Rossi et al., 2014). Rossi et al. (2014) have identified solutions to overcome the short comings of previous DSSs:

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 (Tweeten & Thompson, 2009) which strongly influences the ROI of vertical farms (Shao et al., 2016). 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 (Dania et al., 2018). One DSS has been developed by Zaraté et al. (2019) to engage with the lack of research addressing collaborative planning issues in conventional agriculture (Ahumada & Villalobos, 2009; Tsolakis et al., 2014). The collaborative mechanisms proposed by Zarate et al. (2019) are equally necessary for indoor farming and VF if it intends to provide cities with an alternative source of food.

Indoor Farming Decision Support Systems

There is a wide pool of DSS literature for greenhouse management that could be adapted for small-scale VFs (see Shamshiri et al., 2018). The management of production in a greenhouse is similar to indoor vertical farms and requires decision making on many tasks and time scales (Shamshiri et al., 2018). Decisions are primarily related to management of crop growth conditions, irrigation and propagation (Clarke et al., 1999; Gupta et al., 2010; Pawlowski et al., 2017; Sánchez-Molina et al., 2015; Shamshiri et al., 2018). Greenhouse growers also use prediction tools for disease, yields, production planning, pest management, and cost-benefit analyses (Baptista, 2007; Dimokas et al., 2009; Fisher et al., 1997; Shamshiri et al., 2018). None of these DSS systems adapt to help with the setting up of a farm within an urban context (Manos et al., 2004). A study by Shamshiri et al. (2018), 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.

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 (Agritecture & Autogrow, 2019). 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 1, excluding in-house proprietary software developments by vertical farms (see for example BoweryOS (Kramer, 2018)). 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 (PrecisionAg, 2019). 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.

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 (Brodwin, 2019a; Cohen, 2019). 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 (MIT, 2018) 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" (Kuack & UrbanAgNews.com, 2019).

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 vertical farming 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) (Kuack & UrbanAgNews.com, 2019). 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

Table 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	(Shao et al., 2016)
Liberty Produce UK 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	(Kozai et al., 2015)
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/

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 (Kuack & UrbanAgNews, 2019). 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 is 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 (Kuack & UrbanAgNews.com, 2019)

METHODOLOGY

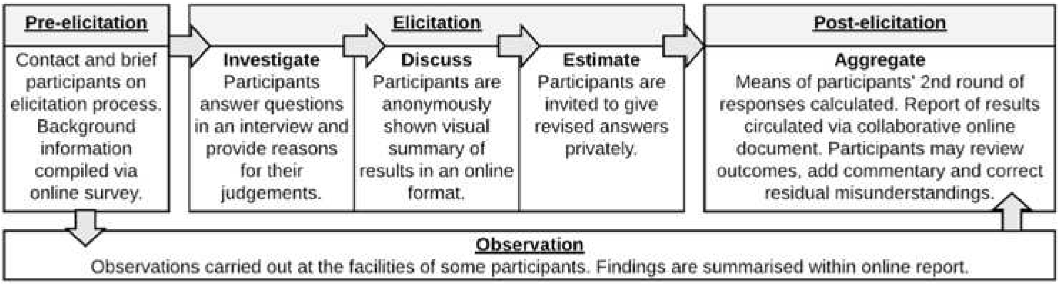
The core aim of the DSS is to provide a robust economic viability assessment, combining user-inputs with historical data gleaned from focused interviews and literature. It is the most complex element and is detailed within this methodology and rationale. This methodology is described into several sections: 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 (Agrilyst, 2018; Agritecture & Autogrow, 2019) and available crop growth recipes (MIT, 2018). 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 (Shao et al., 2016).

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 farm. 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.

Expert Elicitation Protocol With Observations: Investigate-Discuss-Estimate-Aggregate (IDEA)

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 (Hemming et al., 2018), 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

Figure 3. IDEA protocol with integrated observations adapted from (Hemming et al., 2018)



business and industry leaders. It can be adapted to incorporate remote elicitation, making structured expert elicitation accessible on a modest budget (Hemming et al., 2018). It involves several key steps using a modified Delphi procedure (see Figure 3 which has been adapted to include online participation and observations on management practices).

IDEA protocol includes the three-step and four-step elicitation procedure (see example in (Hemming et al., 2018)) 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 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:

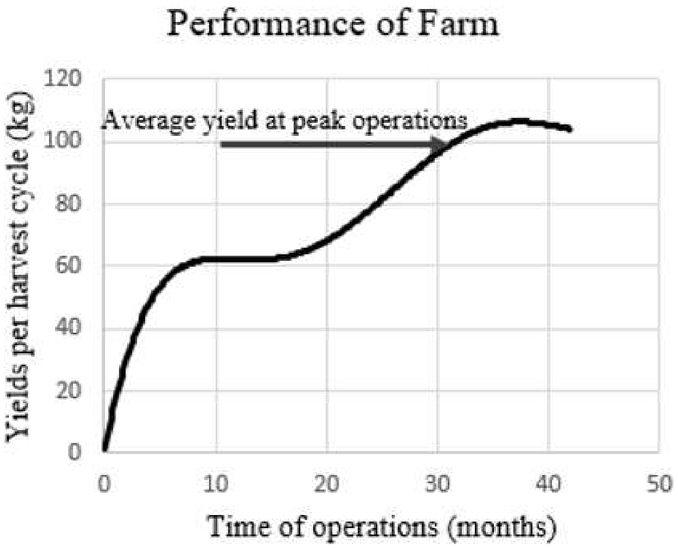
- Time taken to reach peak operational performance or current state
- Increase in yield from the start of operations to peak operational performance or current state (kg or %)
- Lowest yield since running optimally or at current state *
- Highest yield since running optimally or at current state *
- Average yield during running optimally or at current state *
  * *signifies questions which have four-step question format applied in the absence of data*

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.

Imprecise Data Techniques

Due to the current scarcity of data, the imprecise probability technique of probability bounds analysis (Van den Brink et al., 2010) 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 VFs (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

Figure 4. Relationship of average yield over time depicted by a participant



Monte Carlo and will bound the correct answer based on historical case-studies (Van den Brink et al., 2010). Most importantly it only requires partial inputs. It often produces optimal solutions (Van den Brink et al., 2010) and computing with probability bounds allows modelling with significant uncertainty, which in this instance is used to calculate risk in business sustainability.

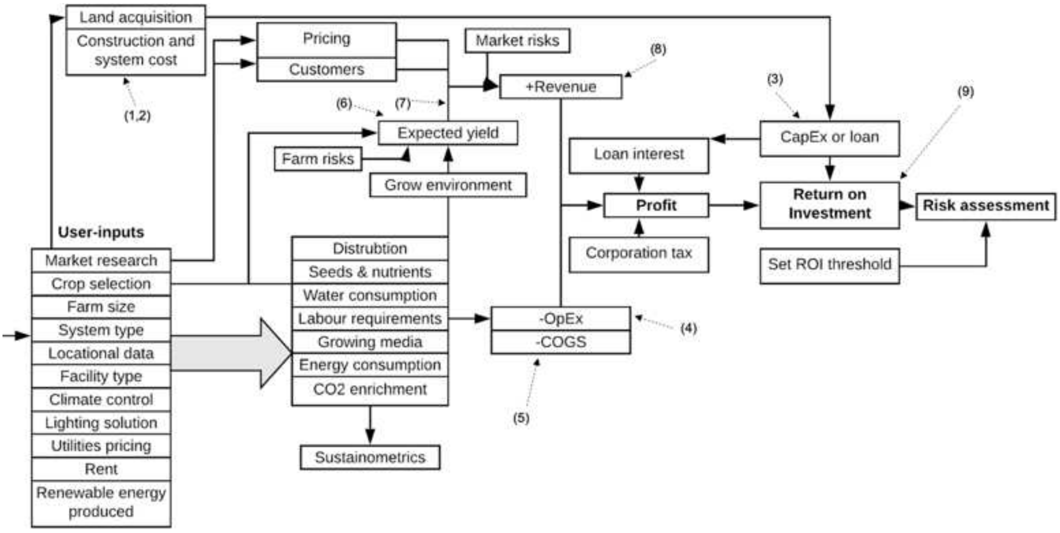
ROI Profitability Model

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 VFs (see (Shao et al., 2016)). Figure 5 illustrates how the model's 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.

Equations 1 and 2 calculate the costs for construction and vertical farming system cost based on the farm design. Equation 3. Calculates the CapEx cost (see Shao et al., 2016 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:

$$\text{Construction cost} = \text{Structure cost} + \text{Finishing cost} + \text{Appliance cost} \tag{1}$$

Figure 5. ROI profitability model utilising equations (1-9) for the risk assessment



System Cost = Light cost + Growing area cost + Germination & clean area cost + Irrigation cost + Processing plant cost + Waste management cost + Renewable energy implementation cost (2)

CapEx = Land acquisition cost + Construction cost + System cost + Reserve fund + Initial working capital + Interests on loan + Depreciation (3)

Equation 4 Calculates the OpEx cost either from user-inputs, or from generalisations based on crops, business model, funding mechanism and farm-type:

OpEx = Lighting cost + Climate cost + Misc energy cost + Water cost + Salaries + Maintenance cost + Rental costs + Distribution cost – Renewable energy + Loan repayment (4)

Equation 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 + CO2_cost + Labour cost + Packaging cost (5)

The yield of a particular plant per harvest cycle is estimated by Equation 6. and has been adapted from VFer (see (Shao et al., 2016)) to compute yield per harvest, with adjustments for nutrients, humidity, light spectra, and risk and uncertainty included:

$$Y_a = Y_s \times N_p \times L_f \times CO2_f \times T_f \times H_f \times N_f \times \left(1 - F_r\right) \times R_f \quad (6)$$

The adjusted plant yield (Y_a) or a plant 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 (Shao et al., 2016). 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 (Siteman & Lysaam, 2019). With artificial lighting, this value should be 1 if lighting is controlled at optimal level.
2. CO_2 factor ($CO2_f$) – 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 (Shao et al., 2016), 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 dependant 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 varys 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 7. This has been adapted from (Shao et al., 2016) 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 PI in Equation 8, which is multiplied by the number of harvest cycles per year to calculate annual revenue:

$$PI_c = P_p \times P_i \times Y_a \times PSR \times CSR \times N_H \tag{7}$$

The plant income per plant for a customer segment (PI_c) is calculated by multiplying the following parameters by the adjusted yield computed from Eqn. 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 (Gordon-Smith, 2019). Noteworthily, crop pricing is extremely dependant on the local market. If the price is specifically known, a value can replace $P_p \times P_i$.
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). (Shao et al., 2016).
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 P_i 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 8. This equation is the summation of all the sources of income for each plant species, denoted as x and their associated customer segments denoted by c. 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:

$$Revenue = \sum_{c=1}^{cust.}\sum_{x=1}^{spec.} PI_{c,x} = \begin{pmatrix} PI_{cx} \\ \vdots \end{pmatrix} \tag{8}$$

Equation 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 Eqn. 5, subtracting OpEx (Eqn. 1), COGS (Eqn. 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:

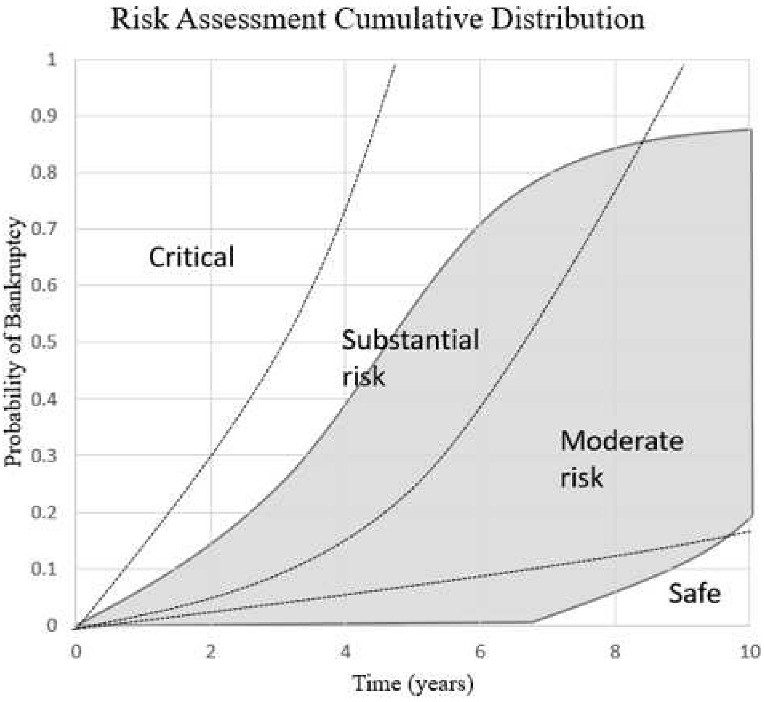
$$ROI = \frac{Revenue - OpEx - COGS - Interest - Tax}{Total\,Investment} * 100 \tag{9}$$

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.

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

Figure 6. Risk assessment graph for the probability of bankruptcy with less precise parameters (cf. Akcakaya, 1992)

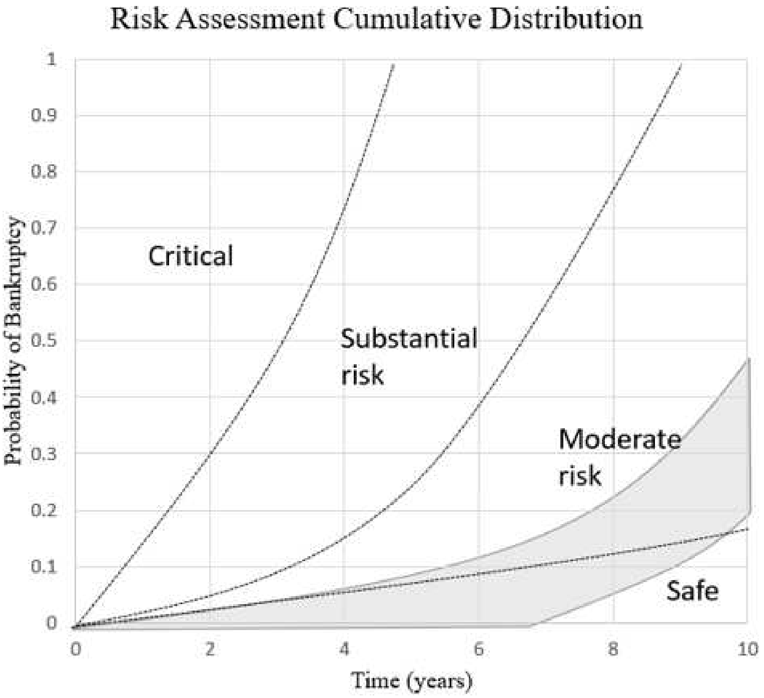


without requiring over-precise assumptions about parameter values or distribution shape (Van den Brink et al., 2010). P-boxes can also be used to model the event of bankruptcy after crossing a threshold defined as the first-passage time, used commonly in economics (Redner & Dorfman, 2002). This approach is assesses the financial risk. Figure 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%+ (Kummer, 2018). 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. 6 and Fig. 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 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 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.

Figure 7. Risk assessment graph for the probability of bankruptcy with more precise parameter inputs (cf. Akcakaya, 1992)



DECISION SUPPORT SYSTEM

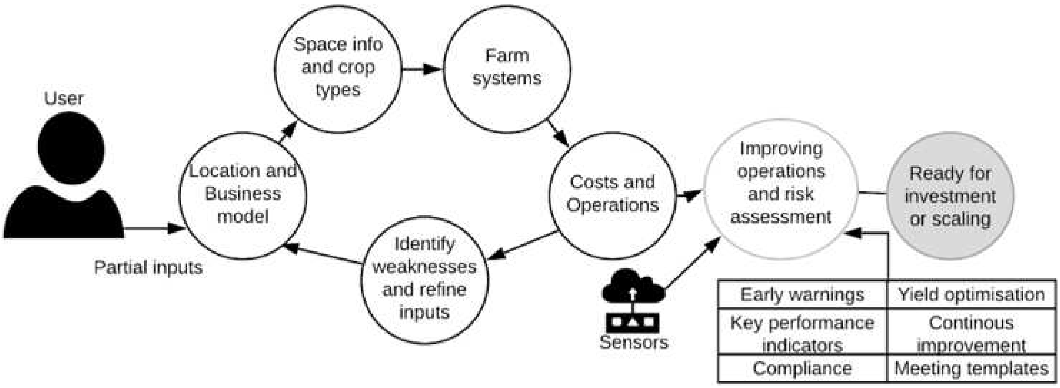
System Process Structure

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" (Shao et al., 2016) 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 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.

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 (Zhang et al., 2015). Figure 9 shows the system process structure of the proposed DSS, which has been adapted from the economic estimation

Figure 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



tool “VFer” (Shao et al., 2016). 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.

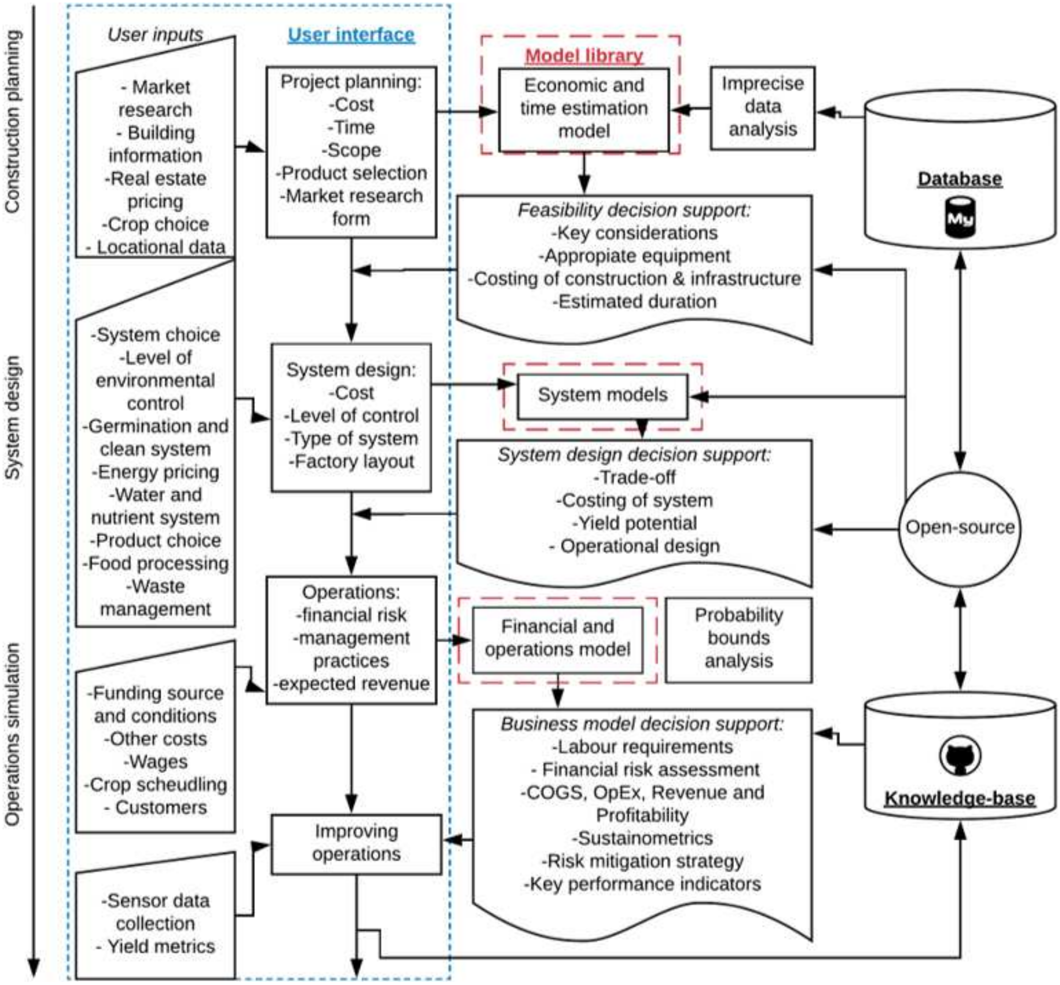
The DSS framework requires only partial information, and highlights gaps where evidence is required. Missing entries are filled with assumptions from the KB and database where possible. The DSS is intended to be a deep-learning tool that enables the users to collate all their information within the same 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 (Ackermann & Eden, 2016; Giordano & Passarella, 2010).

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 (Kuack & UrbanAgNews.com, 2019). 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 (Kuack & UrbanAgNews.com, 2019). The architecture for the database is illustrated in Figure 10. Manual inputs, sensors and processing nodes are integrated to provide environmental information (humidity, temperature, nutrient levels, CO2 and more).

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

Figure 9. System processing structure for the DSS (cf. Shao et al., 2016)

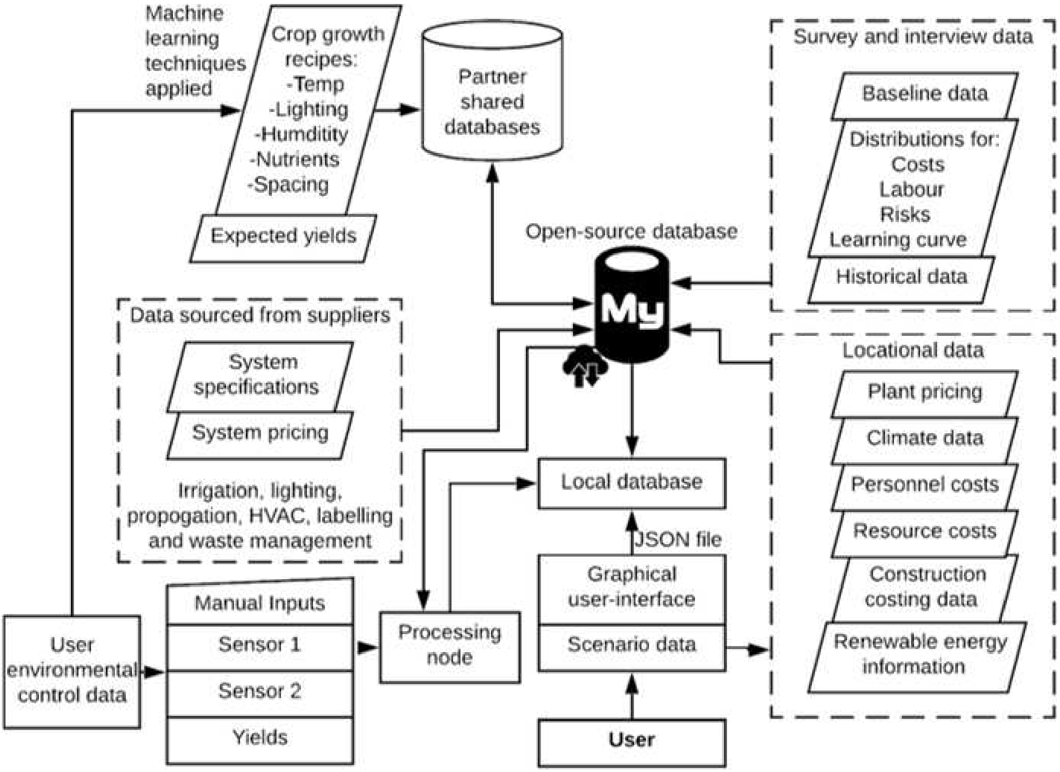


costing data and information on crop requirements, see paper on VFer (Shao et al., 2016). Establishing baseline data for productivity metrics is equally important (AVF, 2017) to drive forward innovation towards sustainability. By developing a database through an open-source approach, the DSS becomes smarter continously. With the capability to self-learn and continuously update, the DSS classifies as intelligent (Tariq & Rafi, 2012). 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 (MIT, 2018) 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.

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

Figure 10. The DSS distributed architecture for database management with a core MySQL open-source database



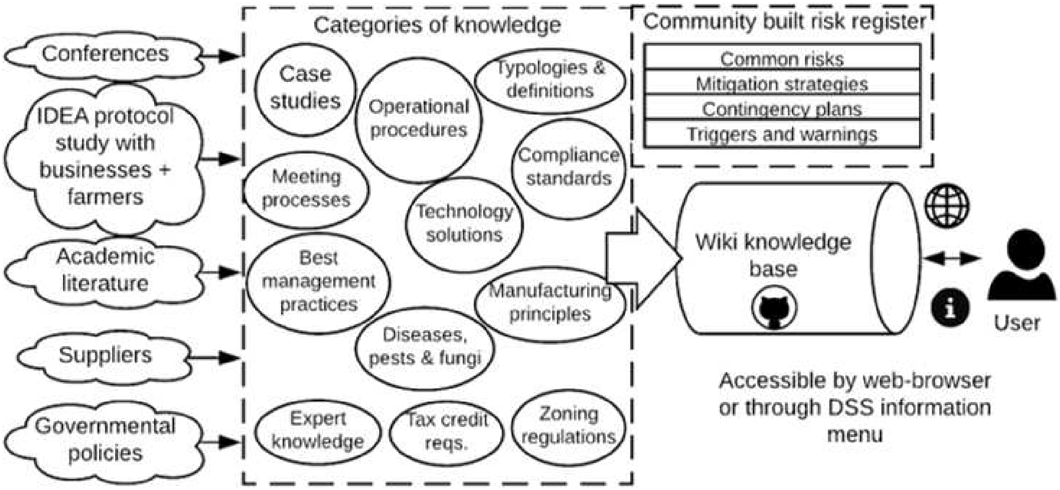
and accelerated knowledge exchange. A Git repository is used via GITHUB for distributed version control and can be found at www.github.com/GaiaKnowledge/VerticalFarming. The KB is either accessible through a web-browser or linked directly through the DSS, acting as a help or additional information menu. 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 (Burwood-Taylor, 2018).

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 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 Denis & Greer, 2018; Liotta et al., 2017; Michael, 2017). 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.

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

Figure 11. Knowledge base wiki-structure with categories of information discovered in an open-source repository



for analysis of data, sensor connectivity and machine learning. The ML structure is broken down into several steps illustrated in Figure 12. The core set of models are part of the financial toolkit described as the ROI and profitability models in Section 3. 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.

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

Figure 12. The ML structure is broken into three steps

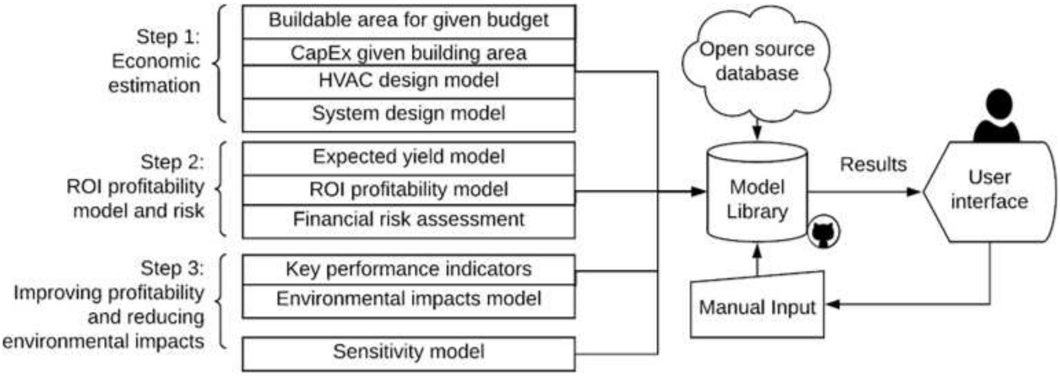
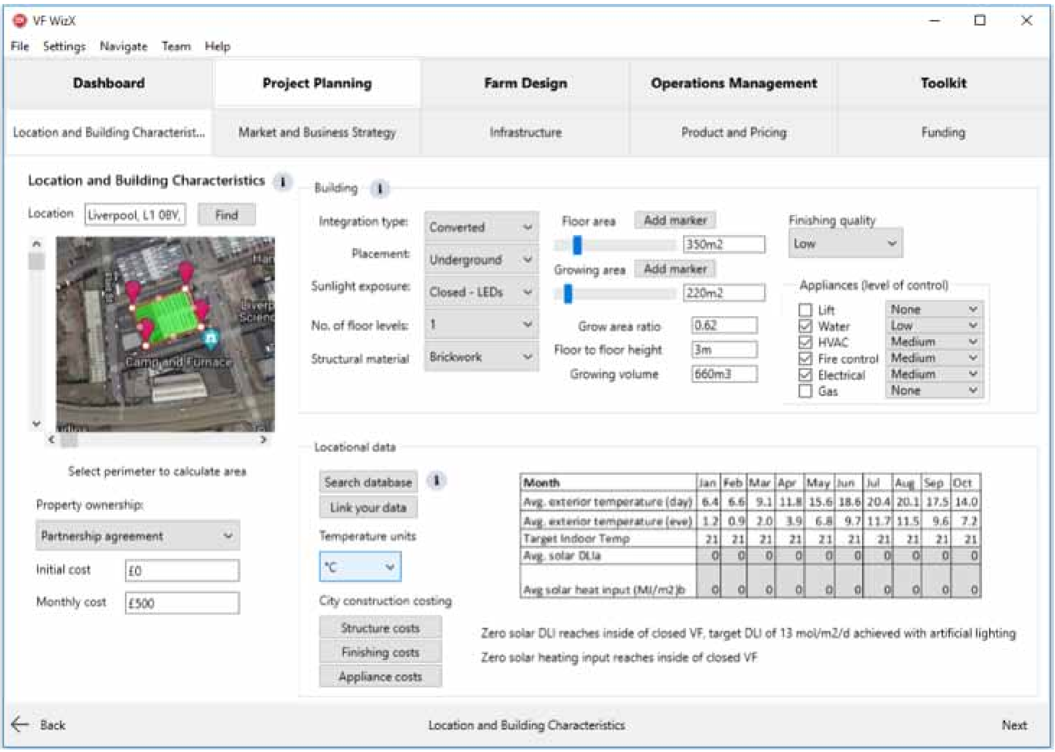


Figure 13. Window for project planning: building and location user inputs of the DSS, Map data from ©2019 Google



Location and Building Characteristics

Location: Liverpool, L1 0BY,

Select perimeter to calculate area

Property ownership: Partnership agreement

Initial cost: £0

Monthly cost: £500

Building

Integration type: Converted

Placement: Underground

Sunlight exposure: Closed - LEDs

No. of floor levels: 1

Structural material: Brickwork

Floor area: 350m2

Growing area: 220m2

Grow area ratio: 0.62

Floor to floor height: 3m

Growing volume: 660m3

Finishing quality: Low

Appliances (level of control)

☐ Lift: None
☑ Water: Low
☑ HVAC: Medium
☑ Fire control: Medium
☑ Electrical: Medium
☐ Gas: None

Locational data

Temperature units: °C

City construction costing

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Avg. exterior temperature (day)	6.4	6.6	9.1	11.8	15.6	18.6	20.4	20.1	17.5	14.0
Avg. exterior temperature (eve)	1.2	0.9	2.0	3.9	6.8	9.7	11.7	11.5	9.6	7.2
Target Indoor Temp	21	21	21	21	21	21	21	21	21	21
Avg. solar DLIa	0	0	0	0	0	0	0	0	0	0
Avg solar heat input (MJ/m2)b	0	0	0	0	0	0	0	0	0	0

Zero solar DLI reaches inside of closed VF, target DLI of 13 mol/m2/d achieved with artificial lighting

Zero solar heating input reaches inside of closed VF

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

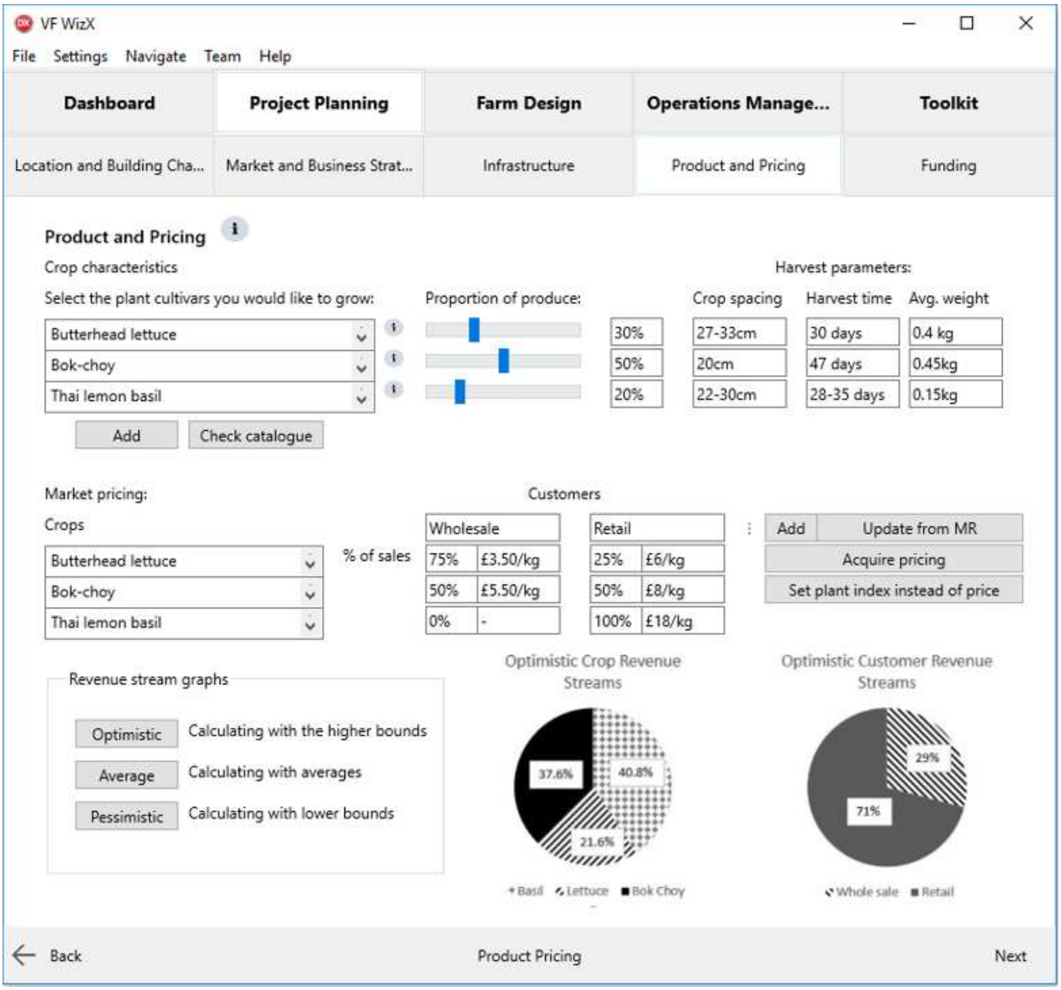
To build a scenario the user opens the project planning tab and proceeds to input details for:

1) Location and building characteristics (see Figure 13)
2) Market and business model
3) Infrastructure
4) Product and pricing (see Figure 14)
5) Funding

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

The database provides a catalogue of crops to choose from, and their typical prices for the country of use (see also (Shao et al., 2016)) for information regarding crop pricing and requirements). Tool tips 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 14. Window for project planning: product selection and pricing



Product and Pricing

Crop characteristics

Harvest parameters:

Select the plant cultivars you would like to grow:	Proportion of produce:	Crop spacing	Harvest time	Avg. weight
Butterhead lettuce	30%	27-33cm	30 days	0.4 kg
Bok-choy	50%	20cm	47 days	0.45kg
Thai lemon basil	20%	22-30cm	28-35 days	0.15kg

Market pricing:

Crops	% of sales	Wholesale		Retail	
Butterhead lettuce		75%	£3.50/kg	25%	£6/kg
Bok-choy		50%	£5.50/kg	50%	£8/kg
Thai lemon basil		0%	-	100%	£18/kg

Revenue stream graphs

Optimistic Calculating with the higher bounds

Average Calculating with averages

Pessimistic Calculating with lower bounds

Parameter Editor

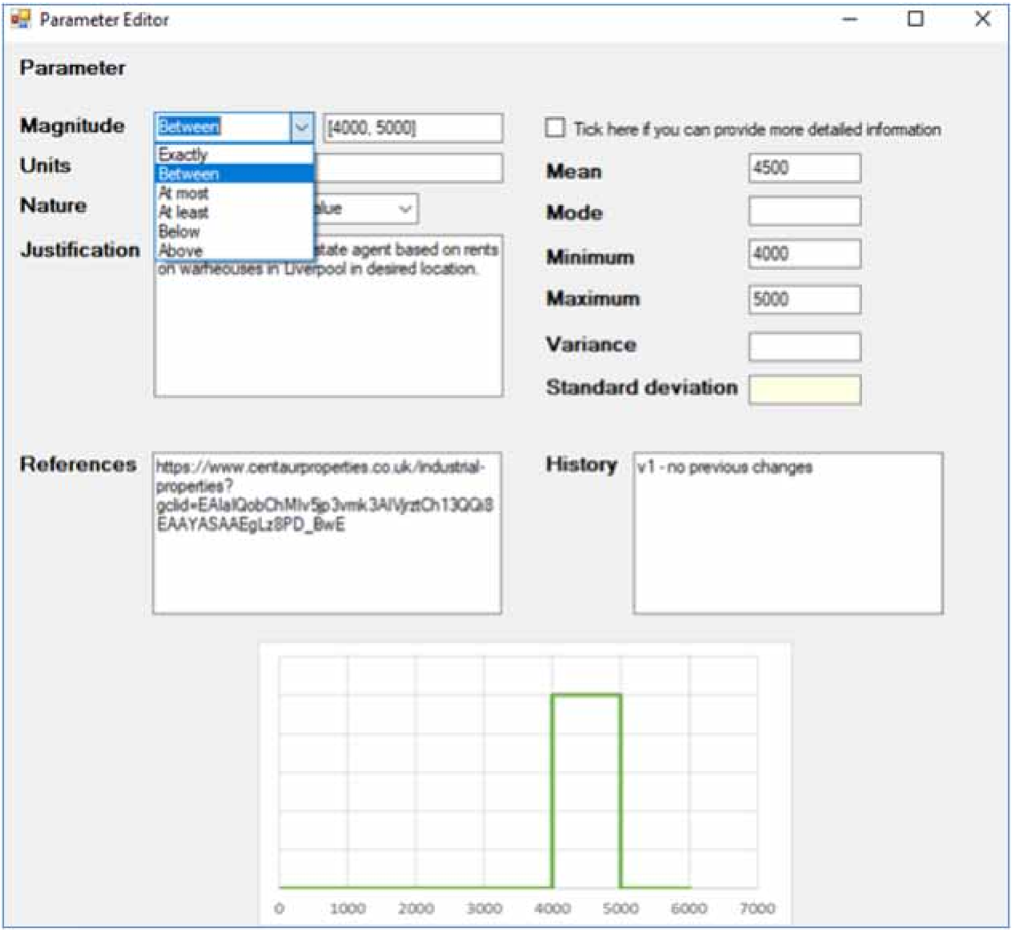
Although fields will be prepopulated where possible, an integral part to the DSS is the parameter editor interface (see Figure 15). It can be opened by double-clicking any field and can self-document any changes the user makes. It accepts linguistic inputs as fuzzy logic (Giordano & Passarella, 2010) 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.

Farm Systems Design

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

1) Irrigation
2) HVAC

Figure 15. Parameter editor that allows self-documentation for any field



Parameter

Magnitude Between [4000, 5000]

Units

Nature ...lue

Justification ...state agent based on rents on warheouses in Liverpool in desired location.

References https://www.centaurproperties.co.uk/industrial-properties?gclid=EAIaIQobChMIv5p3vmk3AIVyztCh13QQi8EAAYASAAEgLz8PD_BwE

☐ Tick here if you can provide more detailed information

Mean 4500

Mode

Minimum 4000

Maximum 5000

Variance

Standard deviation

History v1 - no previous changes

3) Lighting (depicted in Figure 16)
4) Floor layouts
5) Other technology choices

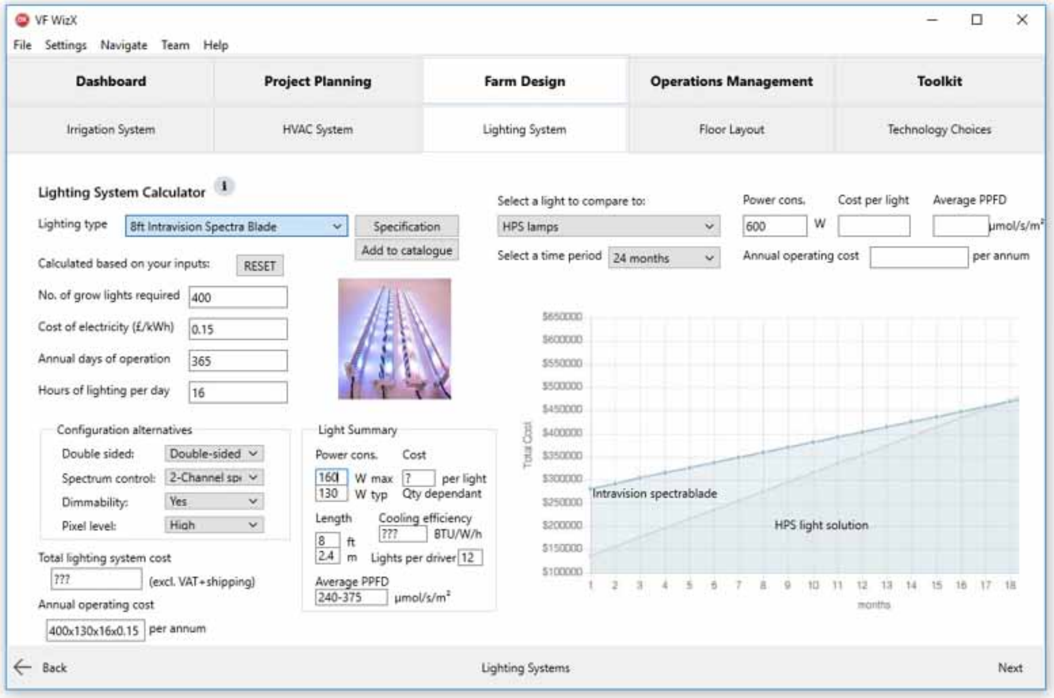
Various lighting solutions can be picked from the database lighting catalogue, or the user can insert their own. Currently the grow light industry is unregulated, and the specifications given by suppliers are not standardised. The mock-up of the lighting window will be used to consult with lighting suppliers 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.

Operations Management

The operations menu has the following tabs:

1) Labour management
2) Crop scheduling
3) Management practices
4) Resource management

Figure 16. Window for farm design: lighting systems for selecting and comparing lighting solutions ©2019 Intravision. Used with permission.



Lighting System Calculator

Lighting type: 8ft Intravision Spectra Blade

Calculated based on your inputs:

No. of grow lights required: 400
Cost of electricity (£/kWh): 0.15
Annual days of operation: 365
Hours of lighting per day: 16

Configuration alternatives
Double sided: Double-sided
Spectrum control: 2-Channel sp
Dimmability: Yes
Pixel level: High

Total lighting system cost: ??? (excl. VAT+shipping)
Annual operating cost: 400x130x16x0.15 per annum

Light Summary
Power cons.: 160 W max, 130 W typ
Cost: ? per light, Qty dependant
Length: 8 ft, 2.4 m
Cooling efficiency: ??? BTU/W/h
Lights per driver: 12
Average PPFD: 240-375 μmol/s/m²

Select a light to compare to: HPS lamps
Power cons.: 600 W
Cost per light:
Average PPFD: μmol/s/m²
Select a time period: 24 months
Annual operating cost: per annum

5) Distribution and sales
6) Utilities management (energy performance is depicted in Figure 17)
7) Sensor integration

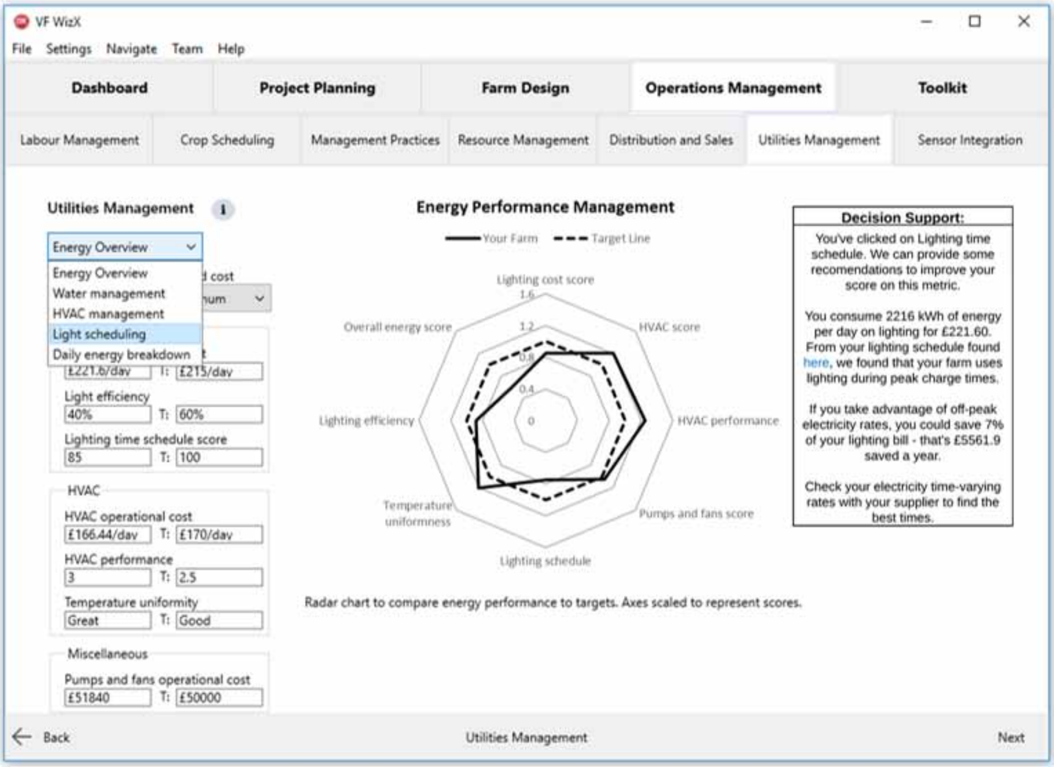
Default values depending on sizing are given for number of hours associated with labour costs for a farm. Decision support can tell users exactly what data they should collect to encourage standardisation and collaboration, a pre-requisite for machine learning. The DSS can model the electricity performance of the user's farm compared to targets set by the user or recommendations from the database. ROI is highly dependent on electricity pricing (Shao et al., 2016) and therefore it is important to encourage measures to reduce this cost.

Toolkit

The toolkit menu contains the following tabs:

1) Feasibility
2) Business model and ROI
3) ROI risk assessment
4) Risk management (see Figure 18 for risk register (Leva et al., 2017; Patterson & Neailey, 2002))
5) Productivity metrics (see Figure 19 for sustainability metrics proposed by (Almeer et al., 2015; AVF, 2017)
6) Team management

Figure 17. Utility management window (cf. Kozai et al., 2015)



Utilities Management

Energy Overview

£221.6/day T: £215/day

Light efficiency
40% T: 60%

Lighting time schedule score
85 T: 100

HVAC

HVAC operational cost
£166.44/day T: £170/day

HVAC performance
3 T: 2.5

Temperature uniformity
Great T: Good

Miscellaneous

Pumps and fans operational cost
£51840 T: £50000

Radar chart to compare energy performance to targets. Axes scaled to represent scores.

Decision Support:

You've clicked on Lighting time schedule. We can provide some recomendations to improve your score on this metric.

You consume 2216 kWh of energy per day on lighting for £221.60. From your lighting schedule found here, we found that your farm uses lighting during peak charge times.

If you take advantage of off-peak electricity rates, you could save 7% of your lighting bill - that's £5561.9 saved a year.

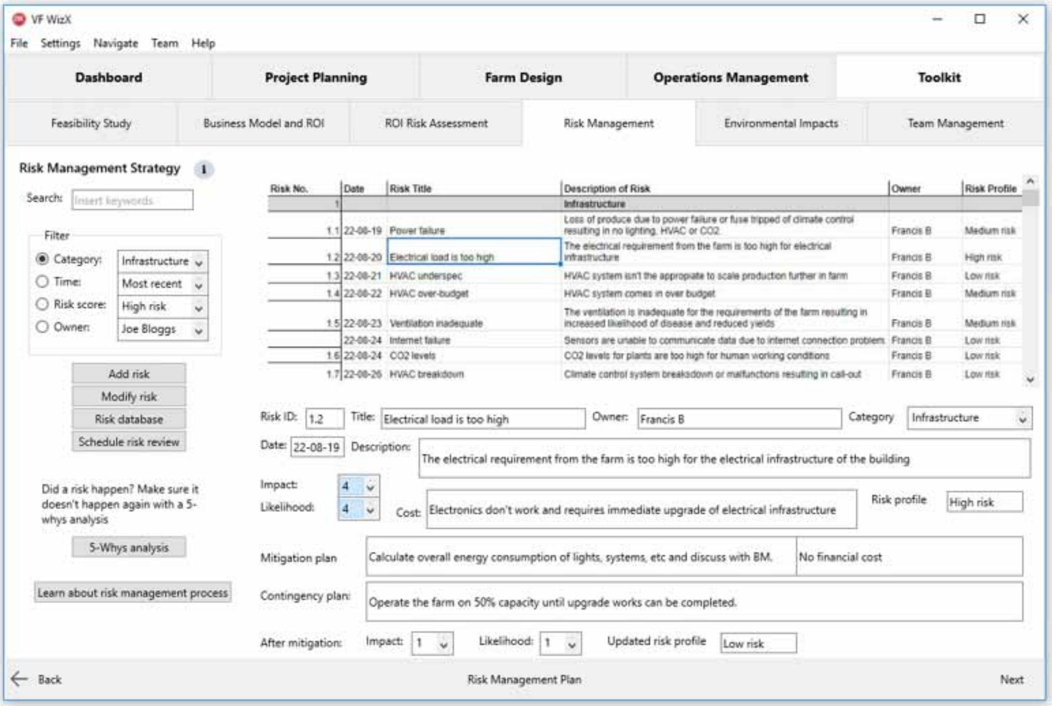
Check your electricity time-varying rates with your supplier to find the best times.

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 (Leva et al., 2017). A built-in meeting scheduler is used to promote group decision-making processes (see Zaraté et al., 2019) with templates such as the five-whys root-cause analysis (see Serrat, 2017) sourced from the KB.

CONCLUSION

The vertical farming (VF) industry will gain further traction in 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

Figure 18. Risk management window within the toolkit tab of the DSS



Risk Management Strategy

Search: Insert keywords

Filter
● Category: Infrastructure
○ Time: Most recent
○ Risk score: High risk
○ Owner: Joe Bloggs

Risk No.	Date	Risk Title	Description of Risk	Owner	Risk Profile
1			Infrastructure		
1.1	22-08-19	Power failure	Loss of produce due to power failure or fuse tripped of climate control resulting in no lighting, HVAC or CO2	Francis B	Medium risk
1.2	22-08-20	Electrical load is too high	The electrical requirement from the farm is too high for electrical infrastructure	Francis B	High risk
1.3	22-08-21	HVAC underspec	HVAC system isn't the appropiate to scale production further in farm	Francis B	Low risk
1.4	22-08-22	HVAC over-budget	HVAC system comes in over budget	Francis B	Medium risk
1.5	22-08-23	Ventilation inadequate	The ventilation is inadequate for the requirements of the farm resulting in increased likelihood of disease and reduced yields	Francis B	Medium risk
	22-08-24	Internet failure	Sensors are unable to communicate data due to internet connection problem	Francis B	Low risk
1.6	22-08-24	CO2 levels	CO2 levels for plants are too high for human working conditions	Francis B	Low risk
1.7	22-08-26	HVAC breakdown	Climate control system breakdown or malfunctions resulting in call-out	Francis B	Low risk

Risk ID: 1.2 Title: Electrical load is too high Owner: Francis B Category: Infrastructure

Date: 22-08-19 Description: The electrical requirement from the farm is too high for the electrical infrastructure of the building

Impact: 4

Likelihood: 4 Cost: Electronics don't work and requires immediate upgrade of electrical infrastructure Risk profile: High risk

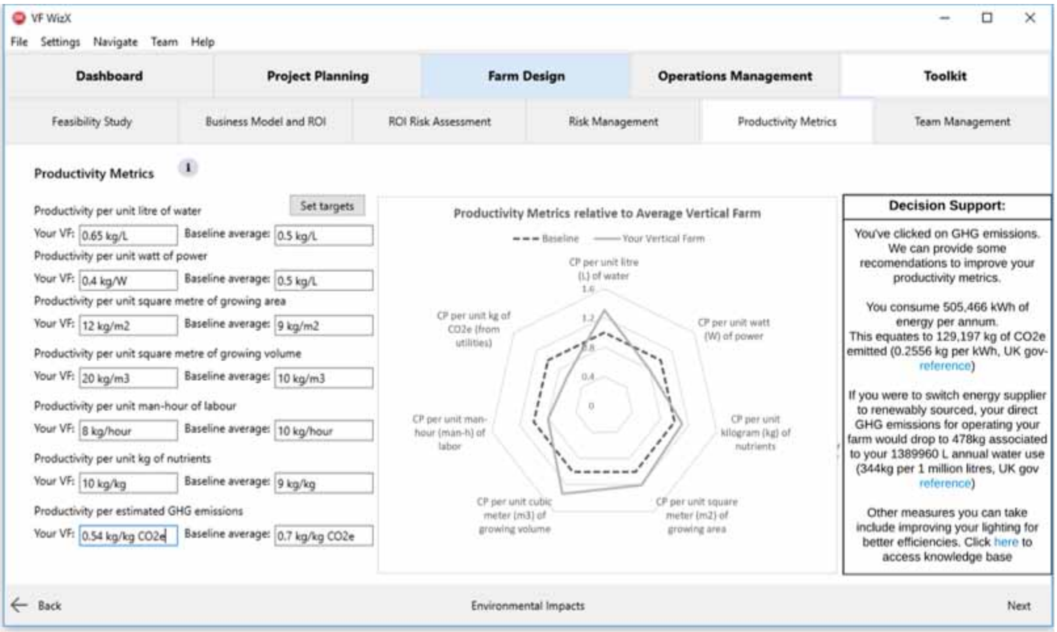
Did a risk happen? Make sure it doesn't happen again with a 5-whys analysis

Mitigation plan: Calculate overall energy consumption of lights, systems, etc and discuss with BM. No financial cost

Contingency plan: Operate the farm on 50% capacity until upgrade works can be completed.

After mitigation: Impact: 1 Likelihood: 1 Updated risk profile: Low risk

Figure 19. Sustainability-based productivity metrics window (cf. AVF, 2017)



Productivity Metrics

Productivity per unit litre of water
Your VF: 0.65 kg/L Baseline average: 0.5 kg/L

Productivity per unit watt of power
Your VF: 0.4 kg/W Baseline average: 0.5 kg/L

Productivity per unit square metre of growing area
Your VF: 12 kg/m2 Baseline average: 9 kg/m2

Productivity per unit square metre of growing volume
Your VF: 20 kg/m3 Baseline average: 10 kg/m3

Productivity per unit man-hour of labour
Your VF: 8 kg/hour Baseline average: 10 kg/hour

Productivity per unit kg of nutrients
Your VF: 10 kg/kg Baseline average: 9 kg/kg

Productivity per estimated GHG emissions
Your VF: 0.54 kg/kg CO2e Baseline average: 0.7 kg/kg CO2e

Decision Support:

You've clicked on GHG emissions. We can provide some recomendations to improve your productivity metrics.

You consume 505,466 kWh of energy per annum.
This equates to 129,197 kg of CO2e emitted (0.2556 kg per kWh, UK gov-reference)

If you were to switch energy supplier to renewably sourced, your direct GHG emissions for operating your farm would drop to 478kg associated to your 1389960 L annual water use (344kg per 1 million litres, UK gov reference)

Other measures you can take include improving your lighting for better efficiencies. Click here to access knowledge base 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 VFs 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 (Hopfe et al., 2005). 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 (Dalal & Singh Chhillar, 2012). 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.

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