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How High is High Enough? Assessing Financial Risk for Vertical Farms Using Imprecise Probabilities

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Method Statement

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 [1] 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 [2].

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 11 which will be explained through a series of equations (S1) through to (S12).

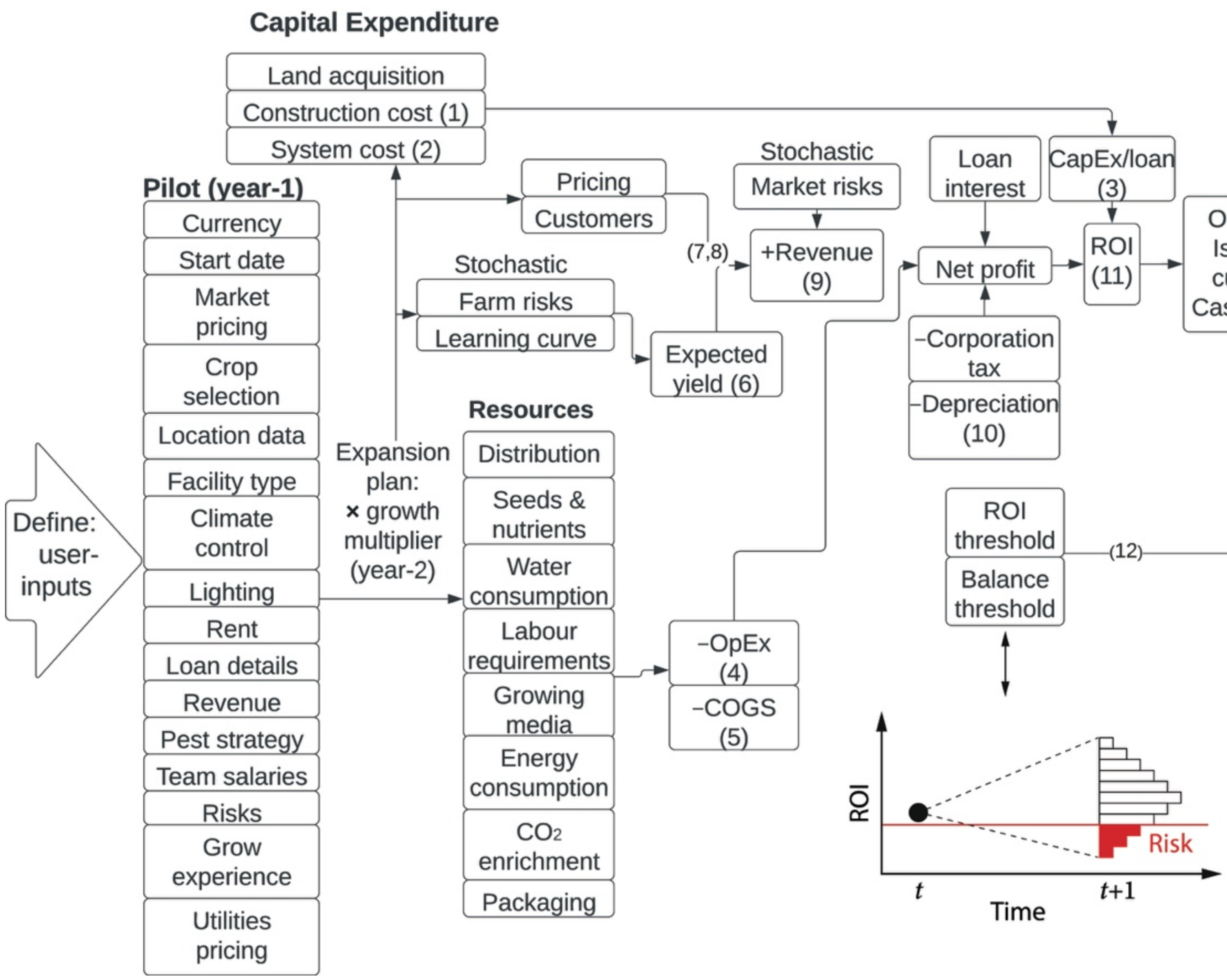

Figure S1. Financial risk model structure (flow left to right) utilising Equations (S1) to (S11)

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 [3] 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 1. of the main article.

$$\text{System costs} = \text{Cold storage} + \text{Lighting system} + \text{Growing system} + \text{Racking} + \text{Germination \& clean area} + \text{Irrigation and nutrient system} + \text{Processing plant} + \text{Waste management} + \text{Renewable energy supply} + \text{Heating, ventilation and air-cooling (HVAC)} + \text{Sensors} + \text{CO2 supply} \quad \text{(S2)}$$

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.

$$\text{CapEx} = \text{Construction cost} + \text{Systems cost} \quad \text{(S3)}$$

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.

$$\text{OpEx} = \text{Rent} + \text{Salaries} + \text{Insurances} + \text{Distribution} + \text{Other costs} \quad \text{(S4)}$$

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.

$$\text{COGS} = \text{Direct labour} + \text{Growing media} + \text{Packaging} + \text{Seeds \& Nutrients} + \text{Electricity} + \text{Water} \quad \text{(S5)}$$

The yield of a particular plant per annum is estimated by Equation S6 and has been adapted from 'VFer' (see [3]) to factor the levels of control in the farm for nutrients, climate control, light control, growing experience and risk.

$$Y_a = Y_s \times A_G \times L_f \times CO2_f \times T_f \times N_f \times (1 - F_r) \times R_f \quad \text{(S6)}$$

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 [3]. 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 [4]. 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 ($CO2_f$) – This is a Yes/No input. The reduction multiplier of yield from insufficient CO_2 enrichment is 0.9. If sufficient CO2 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 [3], 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 [5]. 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 [3], [5] 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.

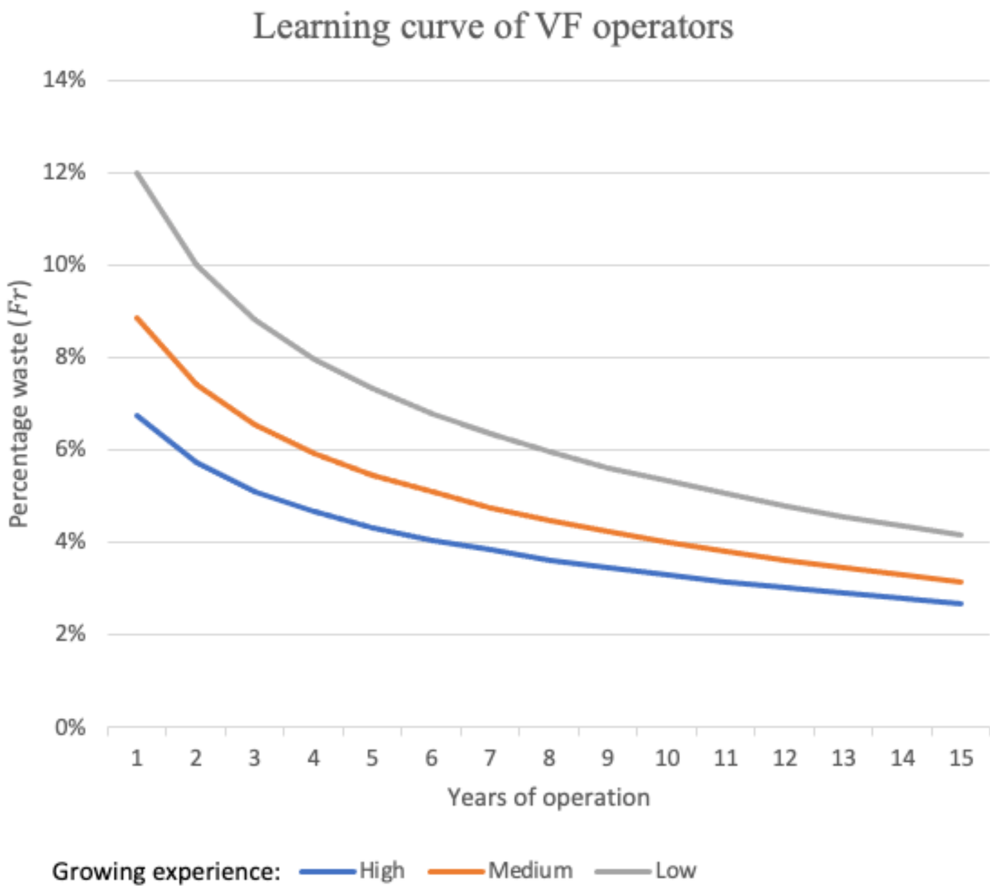

Figure S2. Learning curve of farm operators displaying wastage rate over years of operation (adapted with permission from [5]).

The annual income for a selected crop type is calculated by Equation S7. This has been adapted from [3] to include different customer segments.

$$PI_c = P_p \times P_i \times Y_a \times CSR \quad \text{(S7)}$$

The plant income per plant for a customer segment (PI_c) 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 [6]. Crop pricing is extremely dependant 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.

$$ACI = \sum_{c=1}^{cust.} \sum_{x=1}^{spec.} PI_{c,x} + = \begin{pmatrix} PI_{cx} \\ \vdots \end{pmatrix} \quad \text{(S8)}$$

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 [2]: 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%+ [7]. 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

1.1 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 S1.

Table S1. 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.	[3]
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 fixtures	The number of light fixtures is dependent on the 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.	[3], [8]
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.	[2]
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 m^2 was used.	[10–12]
Adjusted crop yield	Adjusted crop yield estimation is based upon net yield per unit growing area and is reduced by various factors (temperature, light, CO2, etc.) however in reality plant growth is much more nuanced with interdependencies that are difficult to estimate.	[13,14]
Crop risks	Crop risks are influenced by strategic decisions on pest management, level of climate control and level of biosecurity (described further in section 3.2). 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 3.2).	-
System specifications	System specification data (growing systems and LED fixtures) are based upon brochures from suppliers.	[14]

1.2 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.

1.2.1 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 arbitary 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 [15].

$$P(\text{Pest}) = \begin{cases} \text{climate control} = \text{'High' or pest detection} = \text{"Yes"} & 0.5 - 2\% \\ \text{climate control} = \text{'Medium' or pest detection} = \text{"No"} & 5 - 15\% \\ \text{climate control} = \text{'Low'} & 25 - 75\% \end{cases} \tag{S13}$$

$$I(Pest) = \begin{cases} Y_a \times \text{Beta}(a, b) & \text{No pest management} \\ Y_a \times \text{Beta}(c, d) & \text{Pest management} \end{cases} \tag{S14}$$

1.2.2 List of risks

The risks, uncertainties and opportunities (explored in section 2.2 of the article) were incorporated within the model and are defined in Table S2. They are supported from references in the literature and interviews conducted with the purpose of eliciting data [13]. The insights gleaned from interviewing operating and shuttered farm operators informed the causes and associated probabilities and impacts [6]. 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 VFs 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 S2. 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	[6]
Small or big repair	After 2 years, increases with automation level	Repair cost as a fraction of system cost	[16], [17]
Customer withdrawal	Dependant on business model (retail, wholesale, hybrid). Also influenced by competitors in the market place.	Deduction of annual crop income	[6]

Pest outbreak	Low insulation level, low climate control, no integrated pesticide management	Reduction of annual adjusted yield	[6]
Electrical blackout	Aeroponic system without a backup generator. Dependant on location	Reduction of annual adjusted yield (one crop cycle's worth of harvest)	[1]
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	[6], [16]
Funding not acquired	Reliant on acquiring extra funding (grant, loan, etc.)	Expected funding specified in cashflow is not acquired and delayed 1-3 years.	[6], [18]
Wastage rates	Dependant on growing experience	Low experience: Medium experience: High experience:	[1], [6], [16]
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	[1], [6], [16], [19]
Improved labour efficiency	Implementation of manufacturing principles	Potential 2-8% reduction in labour each year resulting in ~50% labour cost reduction after 7 years	[20], [21]
Improved electrical efficiency	Improvements in energy conversion.	Potential 1-3% reduction in lighting energy cost per year	[20]
More efficient LED lighting	New LED lightings acquired after depreciated period	10-40% energy efficiency boost after replacement	[20]

1.2.3 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 S3 shows the pathogen outbreak risk probabilities and impacts.

Table S3. 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	

1.2.4 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 S4 shows the pathogen outbreak risk probabilities and impacts.

Table S4. 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:
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	Minimum= 5% of yield Maximum = 20% of yield Mean = 8% of yield Standard deviation = 3% of yield
Climate control = 'Low' and Insulation level = 'Low' and pest detection = 'No'	40%/year	

1.2.5 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 S5 shows the pathogen outbreak risk probabilities and impacts.

Table S5. 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

1.2.6 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 S6 shows the repairs risk probabilities and impacts.

Table S6. 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% Maximum = 3% Mean = 1.5% Standard deviation = 0.5% Big repairs: Minimum = 1% Maximum = 10% Mean = 4% Standard deviation = 2%
Automation level = 'Medium'	Small repairs = 25% per year Big repair = 1% per year	
Automation level = 'Low'	Small repairs = 20% per year Big repair = 0%	

1.2.7 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 [22]. 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.

1.2.8 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.

2. 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 [13]. It utilises probability bounds analysis combined with first-hitting-time which has been used for other disciplines in ecology and engineering [23]. This novel method is applied to both real-life (UK) and hypothetical (Japanese) vertical farms.

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