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Developing an Economic Estimation System for Vertical Farms

Yiming Shao, University of Nottingham, Nottingham, UK
Tim Heath, University of Nottingham, Nottingham, UK
Yan Zhu, University of Nottingham, Nottingham, UK

ABSTRACT

The concept of vertical farming is nearly twenty years old, however, there are only a few experimental prototypes despite its many advantages compared to conventional agriculture. Significantly, financial uncertainty has been identified as the largest barrier to the realization of a 'real' vertical farm. Some specialists have provided ways to calculate costs and return on investment, however, most of them are superficial with calculations based on particular contextual circumstances. To move the concept forwards a reliable and flexible estimating tool, specific to this new building typology, is clearly required. A computational system, software named VFer, has therefore been developed by the authors to provide such a solution. This paper examines this highly flexible, customised system and results from several typical vertical farm configurations in three mega-cities (Shanghai, London and Washington DC) are used to elucidate the potential economic return of vertical farms.

KEYWORDS

Agricultural Economics, Agricultural Information System, Cost Modeling Methodology, Financial Analysis, Greenhouse, Hydroponics, Simulator, Urban Agriculture, Vertical Farming

INTRODUCTION

The 'vertical farm', a relatively new concept in the realm of urban agriculture that, proposes high-rise buildings as vehicles to cultivate plants in sealed, artificial indoor conditions with advanced greenhouse technologies such as hydroponics and areoponics (Despommier & Ellingsen, 2008). A number of advantages of such a method can be realized compared with conventional outdoor earth-based agriculture. Significantly, these can include:

1. Saving land (stacking up floors and several levels on each floor);
2. All-year-round, high yield production;
3. Protection from severe weather events enabling secured production;
4. No use of pesticides or fertilizers;
5. Saving water (using 70%-95% less water);
6. Saving financial and environmental logistic costs (local fresh production minimizing transportation);
   (Despommier, 2011; Heath, Zhu, & Shao, 2012)

As a result, in the past few years, vertical farms have drawn unprecedented attention from academia to business communities. Despite the aforementioned advantages, proposals are generally still at

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the conceptual stage except for a few experimental small-scale research-based and pilot examples existing in developed countries. Significantly, Heath et al. (2012) identify that the largest barrier to the realization of vertical farming is not the capability or availability of technology, but the uncertainty of its economic feasibility. Since a vertical farm concept integrates multidisciplinary knowledge from architecture and building services to agriculture and other specialist areas, a detailed financial analysis of start-up costs, operation costs, and revenue is difficult to establish. Only a few designers, engineers, economists have made their own approximate calculations either on capital budget or operating costs. Scientist and anti-global warming activist, Monbiot (2010) calculated that the cost of providing enough supplementary light to grow the grain required for a single loaf of bread to be almost \$10 in the US. In addition, according to Omafra (2010), the initial cost could easily be over \$100 million, for a 60-hectare vertical farm. Also, Graff (2011) estimated the return on investment (ROI) for of a 10-storey vertical farm in Toronto to be approximately 8 per cent which is lower than the minimum acceptable ROI, at 10-12 cent, for most investors. These calculations are based on certain particular circumstances, which are difficult to transplant to other cases or locations. The lack of precedent or pioneering examples therefore creates challenges in justifying the ROI for potential developers or investors. Clearly, developers will require some financial evidence before financially committing to the development of detailed design drawings. As a result, without information on the potential ROI, developers and investors are likely to view vertical farm projects as a too risky investment, therefore, a reliable financial estimation tool is required that can overcome the lack of existing detailed design drawings or historical data from similar projects.

Focusing on the above issues, this paper presents an integrated knowledge-based software system developed by the authors, called ‘VFer’ (short for ‘vertical farmer’), to enable better cost and revenue estimations of vertical farms. VFer has two basic functions. The first is for preliminary design estimating, whereby, the user inputs some of the initial decisions and settings of a potential vertical farm project, such as site location, construction information, system selection, plant selection and so forth. Then the VFer system will automatically select the rest of the information necessary for estimating from its knowledge-based library according to user’s choices and restrictions. In this phase, the user’s selections are integrated with expert knowledge, construction codes, current cost data, system performances, labor productivity, and so forth. Finally, a cost and revenue report can be generated. The total processes for this stage can be completed in approximately 3 minutes. The second function of VFer is for a vertical farm project that has a fixed budget. A cost-to-revenue sensitivity analysis will be completed by the system with design alternatives before the optimal solution is provided. VFer will then simulate and present the value of the maximum area of the vertical farm that can be built under constraints of the given budget.

SYSTEM DEVELOPMENT

Conceptual Cost Estimate

According to different planning and design phases, cost estimation can be classified into a number of types. The American Association of Cost Engineers (AACE) lists five types of cost estimates: 1) order-of-magnitude estimate; 2) study estimate; 3) preliminary estimate; 4) definitive estimate; and 5) detailed estimate (Coker, 2007). A conceptual estimation is in between the first and second definition of AACE, which functions as a crucial reference for the investor, contractor, designer or lending entities to evaluate the feasibility and create an initial budget for a project (Sonmez, 2004). VFer is positioned as an evaluation system at a conceptual estimation level and because it will be used at the beginning of project planning, it does not require a detailed design proposal. It can therefore provide flexible design alternatives and a manifestation of associated results as a reference for a user's decision-making process. However, the difficulties and challenges are also obvious during the development of VFer. The conceptual cost estimating models employed needs to comprehensively consider the strategic issues, the limited information, the calculation speed, the control of accuracy, and may also need to assist the estimator in making subjective but reasonable judgments.

Overview of Estimating Methods

A wide range of literature on estimating methods was studied before the development of VFer. Some authors classify estimating methods with estimate levels, such as March (2009), whilst many more focus on techniques, such as the case-based reasoning model (Kim & Kang, 2007), the regression analysis model (Draper & Smith, 1998), and artificial intelligence (AI) modeling methods including expert systems, fuzzy logic, artificial neural network (ANN) and genetic method (Jackson, 1998). Although there are plenty of techniques, they can be categorised into two groups. The first group is an analogous method, vividly called a 'top-down method', which is based on historical data. With a historical data library, the top-down method analyses similarities between the proposed project and projects in the library, and selects those that share the most characteristics, assuming they have similar cost and performance levels. This method can be relatively accurate based on the condition that the library is large enough, and the proposed project type can be found in that library. The other group, a "bottom-up method", uses elemental and parametric techniques to detail the components and then to combine them. This method is effective as long as all the components or attributes are identified and information for each element is available.

The proposal for VFer integrates these two types of methods by dividing the estimation into three key parts: construction; system; and others. Since the vertical farm is a new building typology both in terms of architectural design and construction estimation, its function or cost has never been articulately documented, due to the limited number of practical examples. Therefore, separately computing the main components with a proper method is a relatively accurate and more convincing approach to cost estimation. As such, an analogous method was applied to the construction part, supposing the building as a 'container', while an elemental parametric method was used for the system part, by synthesizing the necessary subsets of the systems applied in a vertical farm. A 'user-defined' method was applied to other costs (such as construction-related costs and capital costs), which are highly dependent upon a user's decisions and preferences.

In general, there were 3 steps in the development of VFer:

Step I - Literature Review and Data Collection

1. Reviewing the research methods associated with cost estimation methods, mathematical / statistical/ analytical methods and so on;
2. Collecting background information on construction, including building structure types, construction project processes in different countries, cost data sources and cost models (building elemental costs for different functional types) and so on;
3. Collecting background information in agricultural science including: unit cost rates of agricultural cultivation service systems; yield of various hydroponic-grown crops under standard conditions (with optimal temperature, humidity and photosynthetically active radiation and proper supply of water and nutrients); the wholesale and retail prices of plants in the market; labor costs; and so on.

Step II - 'VFer' Programming Process

1. Outlining all of the variables that may significantly influence a vertical farm's cost and performance;
2. Creating a built-in database for the input variables and format for output variables;

3. Programming the built-in mathematics and logic interrelationships among these variables;
4. Creating the interface and controlling AI of the program.

Step III - Validation and Analysis

1. Evaluating the accuracy of VFer by comparing the results simulated by the software with actual values from publications;
2. VFer was evaluated by specialists in different fields during and after the Vertical Farming and Urban Agriculture (VFUA) 2014 international conference. The feedback was then collected and analyzed in order to refine the system.

The system processing structures are shown in Figure 1 and Figure 2, which represent the two main functions of VFer. The interactive processes of cost and ROI estimation between the user and system are illustrated in Figure 1. In this function, the user is required to interact with the process by making general decisions, such as whether to apply certain kinds of technologies or design strategies, at different phases. The rest of the information needed will be supplied by the library, which includes detailed values and specifications. Therefore, the requirements of a user's background knowledge are relatively low in operating VFer. Also, help information and warnings are displayed to help the user proceed or prevent any unreasonable decision-making. Based on trials, using VFer takes around 3 minutes to finish the streamlining and achieve the final ROI report. Subsequently, the user can proceed further to sensitivity analysis, which indicates the importance of a group of selected factors that may effectively influence a vertical farm's performance. This sub-function was designed to give the user a better understanding of changes to ROI and budget based upon a changing market.

The second function is the simulation of the maximum buildable area (see Figure 2). Area simulation refers to the previously mentioned second function: whereby given a fixed budget, it can estimate the scale of vertical farm that can be built. To realise this function, firstly, other construction costs and monetary costs were subtracted from the budget to get the value that could be directly spent on construction and systems. After receiving the necessary initial settings (to determine the main strategies) from the user, VFer can then be used to conduct a rough calculation to give a predicted value of area. Subsequently, a method of successive approximations is applied, with 1 per cent iterations. Finally, the maximum value of area (in m^2) is presented with a 'guarantee' that the total budget is not exceeded.

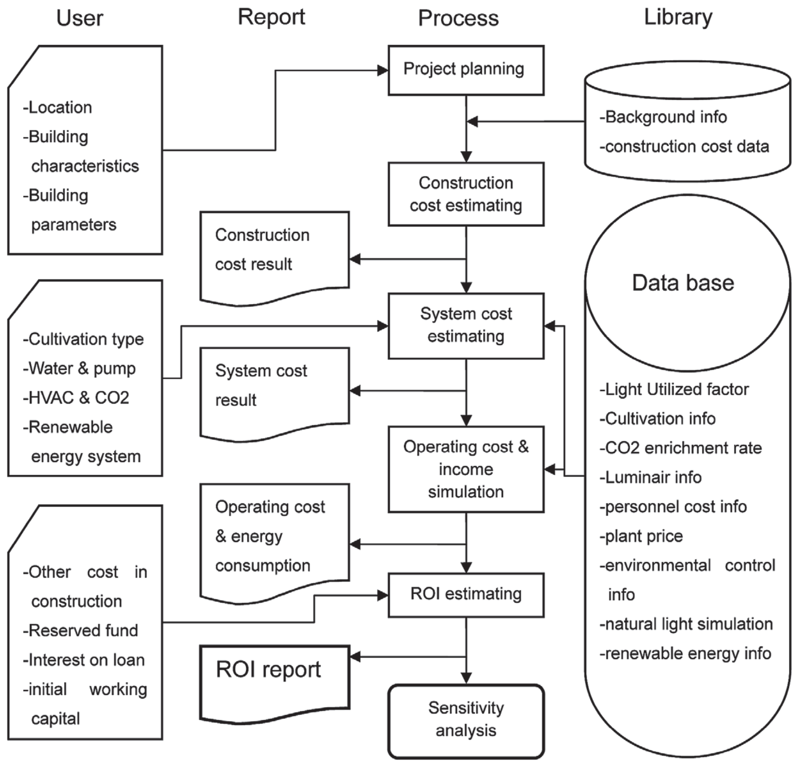
Attributes List

A full attributes list should be the first and most important step of a financial estimate for a vertical farm project. Various forms of estimating manifests or reports can be found from different countries or regions and therefore in order to develop VFer as a uniform system applicable to different locations around the world, whilst not compromising its accuracy, various estimating regulations were investigated and compared. After a study of the typical forms of estimation in the US, UK, and China it was found that the main attributes of construction estimates are basically the same, although differences or sequences can be seen in some subsets (APUC, 2011; GB 50500, 2008; Ohno & Harada, 2006). During the development of VFer, these common attributes were extracted, while differences in some subsets were left to the third part, 'other costs', to enable a user to customize the estimation tool according to their specific needs. The selected attributes and subsets of VFer are:

Part 1 Construction

- Structure:
  - Structural type;
  - Floor area;
  - Floor-to-floor height;

Figure 1. System processing structure of Function 1: cost and ROI estimate



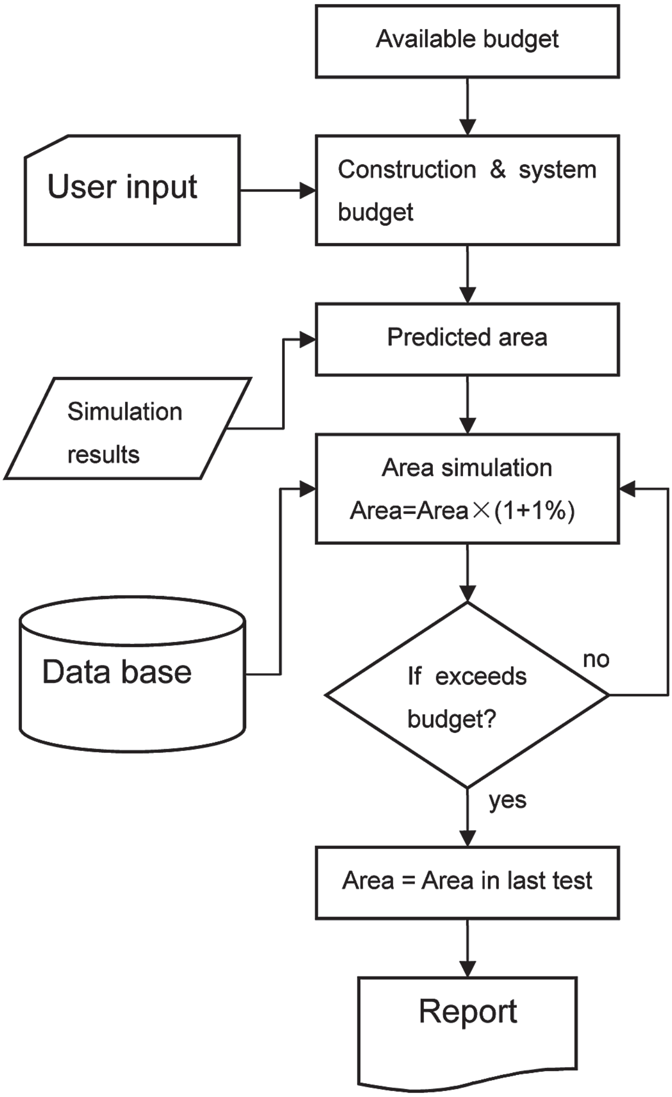
- Number of floors;
- Number of basement levels;
- Width-to-depth ratio.

- Level of Finishes:
  - A combination of factors including: floor, ceiling and façade surface finishes and opening finishes.
- Appliances:
  - A combination of factors including: electrical, water and drainage, gas, fire protection, HVAC, smart control, lift and other appliances.

Part 2 System

- Growth light system:
  - Radiometric watts;
  - Electrical watts;
  - Photosynthetic photon flux (PPF);
  - Power supply efficiency;
  - Growth light price;
  - Life time.
- Growing area system:
  - Growing system;
  - Cooling system, vent door, air circulation;

Figure 2. System processing structure of Function 2: simulation of maximum buildable area



- Testing equipment and growing supplies;
- CO_2 enrichment;
- Insect exclusion.

- Germination and clean system:
  - Sowing machine;
  - Tray cleaning machine;
  - Germination cabins;
  - Others.
- Water and nutrient system:
  - Smart controller;
  - Accumulator tank;

  - Water recovery system;
  - Piping system;
  - Others.
- Food and processing system:
  - Multi-produce washers;
  - Roll stock poly bagger;
  - Stretch wrapping & Produce wrapping;
  - Conveyors;
  - Computer system.
- Waste management system:
  - Biogas digesters;
  - Fermentation tanks;
  - Pipes;
  - Biogas generators;
  - Gas cleaning.
- Renewable energy system:
  - Solar system;
  - Wind system;
  - Hydro system;
  - Biomass system;
  - Geothermal system.

Part 3 Others

- Other Construction Costs:
  - Land associated (demolition, relocation compensation, infrastructure, etc.);
  - Management (tender, temporary structure, survey and design, research and testing, project management, insurance, environmental impact, labor safety and hygiene);
  - Other Fees (joint commission, production preparation, office furniture purchase, etc.).
- Reserved funds;
- Interest on loans;
- Initial working capital.

Creation of the Database

The database comprises of a series of datasets stored in Microsoft Excel files that are used as input information to enable the process of the VF's simulations. Basically, there are two types of data used for the library in the development of VFer: location-related data; and non-location-related data. The location-related data, such as climate, energy price, construction cost, labor cost and so on, varies for different regions in the world. Non-location-related data includes other factors that are not influenced or much less influenced by location, such as the PAR level that a particular species of plant needs for the photosynthesis process, the total illuminance emission by a module of LED growth light, the optimal spacing between two plants using indoor hydroponics, and so on. The location-related data needs to be collected for each potential location, which proves to be time-consuming considering there are a series of datasets and a number of variables in each dataset. Moreover, some of the data can only be acquired by computational simulation, such as building energy consumption and indoor solar radiation on certain surfaces. Therefore, in this pilot study, only three international mega cities, Shanghai, London and Washington DC, were selected as the sample cities to develop the initial library of VFer. The number of locations can be expanded and connected easily into the flexible platform in further research.

Unit Cost of Construction

In the construction cost estimation phase, the conceptual estimate is achieved by multiplying the unit cost rate by the building area. Since the building gross area can be calculated easily, the unit cost rate is the most important variable that may substantially determine the estimating accuracy and as such, published cost models were used in the creation of the datasets. Data collection work commenced with the dataset of Shanghai where the data source was mainly collected from Prices and Indices of Shanghai Construction Works (SCCMIAD, 2012). SCCMIAD (2012) is a government report published by Shanghai Construction & Construction Material Industry Administration Department, which encompasses the latest unit cost rates, such as labor, materials and equipment, and representative cost models of different types of buildings developed from surveys and statistics. The construction cost model composites of the three main parts: structure; finishes; and appliances and installation. The costs of these three parts were calculated separately and then combined to achieve the construction cost estimate. In order to develop the cost model in VFer, seven cost models of different use types, building footprints, and building height (all with relatively large-span spaces) were selected from SCCMIAD (2012) to mimic the similar sized vertical farms (see Table 1).

To create the dataset of the building structure cost, the average structure cost of a car garage and an industrial plant was used to represent a single storey vertical farm, office 1 and office 2 for a multi-storey vertical farm, office 3 and office 4 for a high-rise vertical farm, office 5 for a super high-rise vertical farm, respectively. Unit cost rates shown in Table 1 are based on reinforced concrete. Other material types of structures were predicted based on structure cost comparisons studies (Li & Zhang, 2000; Lau & Yam, 2007; RLB, 2013). The structure costs in Shanghai is shown in Table 2.

Finishing costs fluctuate much more flexibly than the structure cost. These include the finishing work of ceilings and floors, walls and columns, extruded covers, doors and windows, painting or wallpapering, and others. In the creation of finishing cost dataset, the finishing cost values from Table 1 were sorted. The lowest finishing cost for a car garage and the highest value from office 3 were selected to represent the *Very Low* and *Excellent* quality levels respectively. The Other values were created from interpolation calculations to quantify the fuzzy logic method (see Table 3).

Appliances and installation costs cover a series of systems engineering work, including electrical engineering, water supply and drainage, gas supply, fire control, HVAC system, intelligent systems, lift engineering, and others. Much like the construction finishing work, the selection of appliances is highly determined by the client and the designer. Therefore, the cost can also vary widely. In order to measure the representative costs for different appliances and installation quality levels, the cost breakdown in this category of the selected seven cost models was investigated. For each element in the dataset, values were sorted and then the maximum and the minimum value were eliminated. Then the remaining five values, as shown in Table 4, represent the different quality levels. Finally, the values were added up to achieve the total cost.

The basic construction cost, excluding preliminaries and on-site costs, was calculated as:

$$\text{Basic Construction Cost} = \text{Cost}_{\text{structure}} + \text{Cost}_{\text{finishing}} + \text{Cost}_{\text{appliance}} \tag{1}$$

Construction cost estimates of other locations were calculated with reference to Shanghai using international construction comparison survey (Turner & Townsend, 2012). The construction cost of a certain country was calculated as:

$$\text{Cost}_{\text{city } i} = \text{Cost}_S \times \frac{\text{Max Cost}_i + \text{Min Cost}_i}{\text{Max Cost}_s + \text{Min Cost}_s} \times \text{F}_{\text{region}} \tag{2}$$

Table 1. Representative cost models of different types of buildings in Shanghai

	Car garage	*Industrial plant*	*Office 1*	*Office 2*	*Office 3*	*Office 4*	*Office 5*
Number of Storey	4	3	6	8+1 *	15+1	25+2	37+4
Structure type	Frame	Frame	Frame	Frame	Frame-tube	Frame-tube	Braced Frame- tube
Building Height (m)	20.2	14.5	22.8	31.6	64.4	99.7	167.3
Gross Floor Area (m^2)	15060	6708	7675	13067+8176#	22041+4410	37838+7132	71126+23706
Construction Cost (USD)	135.10	123.71	206.23	195.38	269.03	278.82	357.03
Finishing Cost (USD)	56.26	58.05	125.44	191.54	604.14	258.02	225.09
Appliances & Installation Cost (USD)	79.25	21.45	147.12	180.99	241.29	230.02	357.07
Total Cost (USD)	270.60	203.22	478.78	567.91	1114.46	766.86	939.19

Notes: * 8+2 means 8 floors and 2 levels of basement
#13067+8176 means 13067 m2 above the ground and 8176 m2 area of basement
Source: Produced by the authors from SCCMIAD data (2012)

Table 2. Dataset of structure cost in Shanghai

Main Material	*Single Floor*	*Multi-floor*	*High-rise*	*Super High-rise*
Concrete	128	192	272	/
Steel	176	232	314	354
Concrete and Steel	128	192	272	358
Brick	80	86	/	/
Timber	118	176	/	/
Other	160	192	/	/

Note: Values in USD/m^2; Multi-floor = total height below 24 m; High-rise= total height between 24m to 100m; Super High-rise = total height > 100m

Table 3. Dataset of finishing costs in Shanghai

Finishing Quality	*Very Low*	*Low*	*Medium*	*High*	*Excellent*
Cost per m^2	54.40	192.00	329.60	464.00	600.00

Note: Values in USD/m^2

Table 4. Dataset of appliances and installation cost in Shanghai

Appliances	*Very Low*	*Low*	*Medium*	*High*	*Excellent*
Electrical	16.48	67.36	70.56	73.76	102.40
Water	9.12	9.12	9.12	12.64	25.60
Gas	/	/	/	/	/
Fire Control	7.84	18.08	19.68	24.96	29.76
HVAC	/	48.16	50.24	61.92	65.76
Intelligent Systems	/	5.92	24.96	37.92	64.80
Lift	/	8.96	18.40	19.04	21.28
Total	33.44	157.60	192.96	230.24	309.60

Note: Values in USD/m^2

Where $\mathrm{Cost}_{\mathrm{city}\ i}$ is the construction cost of the target city; Cost_S is the construction cost for Shanghai (either structure, or finishing or appliances and installation cost); $\mathrm{Max\ Cost}_i$ is the typical unit cost rate of an office in a business park and $\mathrm{Min\ Cost}_i$ is the typical unit cost rate of a warehouse in the target country; $\mathrm{Max\ Cost}_s$ and $\mathrm{Min\ Cost}_s$ are unit cost rates for an office and a warehouse in Shanghai, respectively. These values are given in USD per square meter for the year of 2012 in Turner & Townsend (2012); $\mathrm{F}_{\mathrm{region}}$ is an adjustment factor which reflects the construction cost difference between the target city and the capital city of the country or mega cities in that country. If the target city is the capital city or a metropolitan economically alike, $\mathrm{F}_{\mathrm{region}}$ equals to 1. Otherwise, $\mathrm{F}_{\mathrm{region}}$ should be calculated with further information of cities' comparison surveys.

Information on Growing and Service Systems

The unit costs of the growing system, including the growing set, the HVAC system, the environmental controls, the electrical panel and technical support, the growing supplies, the CO2 enrichment, and the insect exclusion, were collected from CropKing (2013). The unit costs of the germination and cleaning system, the water and nutrient systems, and the food processing system were collected from Banerjee (2012). Information on grow lights was collected from selected manufactures' (Philips™ and Illumitex™) product brochures including datasets on the Photosynthetic Photon Flux Density (PPFD), the radiometric watts, the electrical watts, the life time, and the price of the luminaire. Information on renewable energy systems and energy production were collected from IRENA (2013).

Information on Plant Cultivation

In order to simulate the annual yield of different crops and thus to predict the revenue of a vertical farm, a dataset that contains the information on plant cultivation is necessary. This dataset provides the input values of a series of fundamental variables, such as photosynthetically active radiation (PAR), photoperiod (how many hours the plant needs to be exposed under the rated PAR), the germination and growth period, and so on. In order to estimate the operating cost, another group of variables are needed, such as water usage, plant spacing, the distance between the growth light and the plant canopy, and so on as shown in Table 5.

During the creation of this dataset, the method of information capture was diverse but applied in a sequence. The first step was searching for published papers in academic journals to examine whether there is any scientific research of hydroponics for the selected plant species. If there is any necessary,

Table 5. Information on plant cultivation

Plants	*PPFD µmol / m2/s*	*PAR mol/ m2/ day*	*Photop-eriod hours*	*Days before Harvest*	*Dry Mass/ plant kg*	*DM:FM*	*Plants/ m²*	*Gross yield kg/ m2/ year*	*Water L/DM kg plant*	*FM per plant kg*	*Water Use L/ M²/ year*	*Plant spacing m*	*Height of shoot m*	*Depth of root m*	*Light Use Efficiency kg/mol/m2*	*Harvest Index*
Tomatoes	313	13.5	12	75	0.291	0.060	4.8	113.1	300	4.9	2036	0.5	1.2	0.2	0.0242	0.50
Lettuce (butterhead)	295	17.0	16	30	0.007	0.048	43.1	78.5	402	0.1	1515	0.2	0.2	0.2	0.0127	0.67
Spinach	295	17.0	16	30	0.002	0.080	43.1	10.5	402	0.0	337	0.2	0.1	0.2	0.0017	0.67
Cucumber	250	16.2	18	58	0.331	0.045	1.7	80.4	172	7.4	618	0.8	1.5	0.3	0.0136	0.20
Broccoli	250	10.8	12	64	0.085	0.090	4.8	25.7	198	0.9	458	0.5	0.5	0.4	0.0065	0.33
Celery	250	14.4	16	97	0.034	0.050	43.1	110.2	450	0.7	2480	0.2	0.4	0.2	0.0210	0.75
Eggplant	250	10.8	12	81	0.108	0.080	4.8	29.0	198	1.3	459	0.5	0.6	0.1	0.0073	0.33
Lettuce (Iceberg)	250	14.4	16	73	0.018	0.040	15.5	56.6	402	0.5	565	0.3	0.3	0.2	0.0108	0.67
Sweet Pepper	250	10.8	12	68	0.101	0.100	10.8	58.4	150	1.0	876	0.3	0.8	0.2	0.0148	0.25
Bok-Choy	295	17.0	16	49	0.030	0.080	24.2	67.6	402	0.4	2173	0.2	0.3	0.1	0.0109	0.67
Strawberry	255	11.0	12	85	0.042	0.080	10.8	24.1	198	0.5	382	0.3	0.2	0.2	0.0060	0.33
Watermelon	350	15.1	12	85	0.960	0.080	0.7	34.7	198	12.0	549	1.2	0.6	0.3	0.0063	0.33
Chinese Leaf	295	17.0	16	85	0.084	0.070	15.5	79.8	480	1.2	2681	0.3	0.3	0.1	0.0129	0.80

Note: DM = Dry Mass; FM= Fresh Mass; the Light Use Efficiency represents the fresh mass of fruits harvested per unit PAR every square meter; Harvest Index is the ratio that edible weight to the gross harvest weight
Source: Author produced according to various publications and databases

then the input/output data from that paper were extracted and applied in the dataset. For instance, there is research data on the growth of lettuce (A. Shah & S. Shah, 2009; Li & Kubota, 2009; Lina et al., 2013); data on the growth of tomatoes (Fan et al., 2013); and data on the growth of cucumbers (Grewal, Maheshwari, and Parks 2011). If there was not such data available, then online databases, research reports, handbooks and theses were searched. For instance, Both (2002) presents a regression model on the growth of lettuce, whilst Molinar, Yang, & Moura (2005) indicate the cost and return of producing cherry tomatoes, and Alexander (2013) produced a growing guide for a number of different vegetables and crops. The third step in this search meant acquiring the remaining data from abroad study of other media, such as websites that contains hydroponic information, manufacturers' brochures, homegrown societies, and so on. The final data sources referenced for the creation of database are summarized in Table 6.

Simulation on Heating and Cooling Loads

The energy consumption of the environmental controls (heating and cooling loads) varies even if the same building configuration is applied to different climatic zones. In order to achieve relatively accurate values of energy consumption of the environmental controls, five variables were selected for parametric tests of benchmark vertical farms in different configurations and locations. Descriptions on variables and initial settings are shown in Table 7. Computational simulations were conducted over 200 times using Autodesk Ecotect® software in order to create a data library where the simulation results of the benchmark vertical farms (in kWh/m^2/year) can be representative to those of the target VF which has similar specifications.

Simulation of Solar PAR on Growing Trays

Unlike the artificial lighting type of vertical farm where the PAR on plants is controlled by electric power, PAR in a sun-fed vertical farm is mainly determined by the insolation of natural light, which

Table 6. Data sources on plant cultivation

Plants	*Data Sources*
Tomatoes	Fan et al. (2013) ; Banerjee (2012) ; Alexander (2013) ; Holliman (2006) Bastin & Henken (1997) ; Willis (1992)
Lettuce (butterhead)	Li & Kubota (2009) ; Lina et al. (2013); Brechner and Both (1998) ; Albert (2011)
Spinach	Banerjee (2012) ; Alexander (2013) ; Willis (1992) ; Albert (2011)
Cucumber	Grewal et al. (2011) ; Bastin & Henken (1997) ; Albert (2011)
Broccoli	Le Strange et al. (2010) ; Alexander (2013) ; Bastin & Henken (1997) ; Albert (2011)
Celery	Alexander (2013) ; Bastin & Henken (1997) ; Albert (2011)
Eggplant	Bastin & Henken (1997) ; Islama et al. (2010) ; Willis (1992)
Lettuce (Iceberg)	Banerjee (2012) ; Both (2002) ; A. Shah & S. Shah (2009) Bastin & Henken (1997) ; Willis (1992)
Sweet Pepper	Banerjee (2012) ; Willis (1992) ; Albert (2011)
Bok-Choy	Pant, Radovich, & Arancon (2012); Zhu, Gerendas, & Sattelmacher (1997) ; Cho & Son (2007) ; Willis (1992)
Strawberry	Banerjee (2012) ; Bastin & Henken (1997)
Watermelon	Bastin & Henken (1997) ; Willis (1992) ; Albert (2011)

Table 7. Descriptions on variables and settings

Variables	*Description*
Scale of floor area	Three scales: 10m×10m; 20m×20m; 40m×40m;
Building height	Three levels: ■ Single floor – less than 10m; ■ Multi-floor – 6 floors; ■ High-rise – for 10m×10m footprint, N/A*; for 20m×20m footprint, 20 floors; for 40m×40m footprint, 30 floors
Insulation level	Three levels: ■ Poor insulated – 220 mm brick (U-value 2.02 $W/m^2.K$) ■ ETFE (transparent) – double skin (U-value 1.6 $W/m^2.K$) ■ Well insulated – 150 mm foil-faced, glass-fiber, 75 mm air gap, 110 mm brick (U-value 0.12 $W/m^2.K$)
Air change rate per hour (ACH)	Three levels: ■ Air tight – 0.25 ■ Medium – 0.5 ■ Normal -1
Power of growth lights in W/m^2	Three levels: ■ Sun-fed type – 0 W/m^2 ■ Artificial lighting 4-6 layers of growing trays – 200 W/m^2 ■ Artificial lighting 6-8 layers of growing trays – 300 W/m^2
Other settings	Floor to floor height is 4.5 m Temperature range: 18-30 °C

* 10m×10m footprint may not have a high-rise configuration due to structural stiffness

fluctuates daily. Therefore, it is necessary to simulate how much PAR there will be on growing trays with different orientations and height levels to estimate the annual yield and revenue. In order to fulfill this objective, three configurations of sun-fed vertical farm, A-frame, façade system and columnar system, were simulated separately using the Solar Access Analysis tool in Autodesk Ecotect ®.

Figure 3 shows an example of the 3D model of an A-frame vertical farm used for simulation purposes. One of the middle frames (the second one from the east) was selected for the simulation because it is an ideal representative of the average situation where middle frames may be somewhat shaded by the frames on both sides. Finally, the simulation on each separate layer of the frame was conducted.

Calculation Process

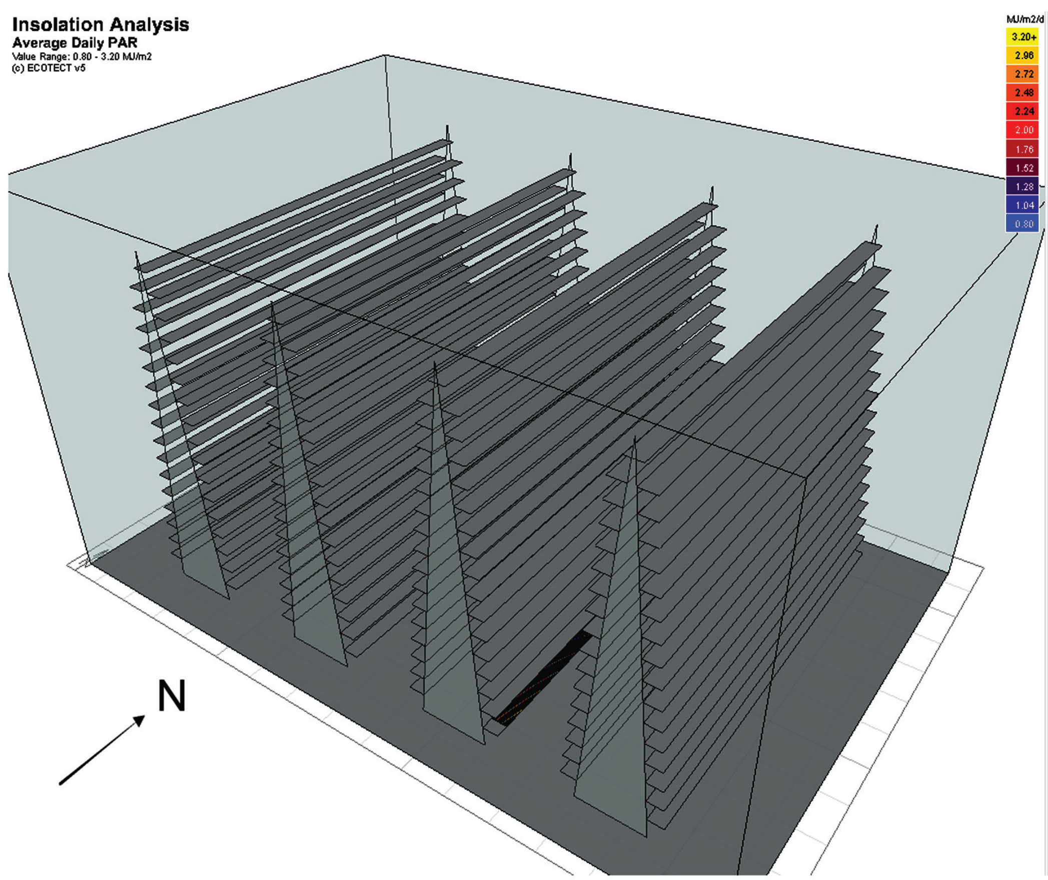
In VFer, the most used of the models in calculating the costs are rooted on the principle of the quantity of work or material and the unit cost rate (Skitmore & Marston, 1999).

$$C = \sum_{i=1}^{n} q_i \cdot r_i \tag{3}$$

Where C is the total estimated cost; q_i is the quantity of work i (representing the floor area or growing area in units of square meters); r_i is the unit cost rate of work i (cost or energy consumption per square meter), which comes from the created database.

There are 5 steps to achieve the total capital cost.

Figure 3. 3D model of A-frame prototype in Ecotect ® Solar Access Analysis ®



Step 1:

The land price, representing the average price of business parks in the peri-urban area, was collected from commercial surveys in order to calculate the Land Acquisition Cost.

Step 2:

Calculating the construction cost:

$$\text{Construction Cost} = \text{Structure Cost} + \text{Finishing Cost} + \text{Appliance Cost} \tag{4}$$

Step 3:

Calculating the system cost:

$$\text{System Cost} = \text{Grow Light Cost} + \text{Growing Area Cost} + \text{Germination \& Clean Cost} + \text{Water \& Nutrient Cost} + \text{Food Processing Cost} + \text{Waste Management Cost} + \text{Renewable Energy Cost} \tag{5}$$

Step 4:

Calculating other costs including other construction costs, reserve funds, interests on loans, and initial working capital. As aforementioned, these sub-items are highly user-defined, although some suggested values are provided by the system.

Step 5:

As the entire sub-items of systems were calculated, the total cost can be achieved by adding them up as:

Total Capital Cost = Land Acquisition Cost + Construction Cost + System Cost + Other Construction Cost + Reserve Fund + Interests on Loan +Initial Working Capital (6)

Then, the annual operating cost can be calculated as:

Operating Cost = Bill_Growth_Lights + Bill_Environmental_Controls + Bill_Miscellaneous_Energy + Water Bill + Seed Cost + Nutrient Cost + Personnel Cost + Maintenance Cost+ CO_2 Cost - Reduction from Renewable Energy (7)

The annual yield of a particular plant is:

Adjusted Plant Annual Yield = Standard Annual Yield × Plant Area × PAR Factor × Increment by CO_2 Enrichment × (1- Failure Rate) × Temperature Factor (8)

Where the Standard Annual Yield is the validated value from literature which is recorded in Table 4; the PAR Factor is a ratio of the actual PAR delivered to the plants' canopy to the theoretical PAR requirements. For an artificial lighting type of vertical farm, the value was 1, which means the PAR can be always controlled at the optimal level. However, for sun-fed types, the value of actual PAR was acquired by Ecotect ® simulations. Temperature Factor is a factor that reflects the reduction of yield caused by overheating or freezing of the growing area if the indoor temperature is uncontrolled by HVAC or other systems. The value was set as 0.9 for the preliminary estimation; Failure Rate was set as 5%.

Therefore, annual income from plant production is:

Plant Annual Income = Plant Price × Price Index × Adjusted Plant Annual Yield × Price Share Rate (9)

The Price Index is the ratio that the price of products from a vertical farm to the average retail price from current market. This was set at 1 if not specified by the user. The Price Share Rate is the ratio that the revenue is shared between the farm and other marketing process. This was introduced to reflect the potential cost savings of transporting produce to market from rural farms and from the reduction in food supply chain that are significant cost savings but cannot be directly included at this stage due to the wide range of locations of the source of traditionally grown produce (Bloom & Hinrichs, 2011). If not specified by the user, the Price Share Rate was set at 0.6 (approximately three times as high as rural farms), assuming 60% of the revenue will be shared by the farm.

Operation of the System

VFer processes the following sequence:

1. The user selects the location of the proposed project. Initial settings are automatically imported by the system, although all the values can be reassigned by the user if necessary.
2. The user determines the main strategies of the project and specifies the parameters of the building.
3. The user determines the technology strategies which encompass the type of energy input (the artificial lighting type or the sun-fed type), the water recycling method, the HVAC system, the CO_2 enrichment, and the application of renewable energy systems.
4. The user determines the plant types to be grown and the percentage of each plant type. VFer will automatically filter plants that are not suitable for the selected cultivation framework.
5. The user determines the percentage of construction cost and monetary costs.
6. VFer displays the ROI result and cost breakdown charts for both fixed costs and operating costs (see Figure 4 as an example). Then a full report can be created automatically.
7. VFer conducts a sensitivity analysis on the ROI test and the Budget test. Two sensitivity charts are then created to show the effect of changing the 12 selected factors on the ROI or the total budget.

Validation

It is not yet possible to validate VFer against a completed 'real project' since there is no published data available. Even if available, considering the great flexibility of VFer, segments of news or pieces of information are far less than required for full validation needs, because:

- The simulation results depend on many parameters and different settings that may lead to totally different results;
- As a new typology, the vertical farm is still 'under testing'. 'Real-time' data could therefore reveal information or even commercial secrets hence the unavailability at present of the limited data that may exist. Besides, if test results are not stable, they still cannot be used in the validation process.
- Some external factors, such as plant prices, are changing all the time and can be considerably different from place to place. The simulation may therefore have some 'lags' compared to the latest circumstances.

Instead of validation as a 'whole', VFer was validated 'part-by-part'. For instance, in the construction estimation part, data from Turner & Townsend (2012) were used for the cross validation (See Table 8).

Mean absolute percentage error (MAPE), the most important parameter for accuracy evaluation, was used to examine the model effectiveness by applied to different cases (An et al., 2007). It can be obtained using Equation 10:

$$\mathrm{MAPE} = \left(\sum_{i=1}^{n} \frac{x_i^{'} - x_i}{x_i} \times 100\% \right) / \, n \tag{10}$$

Where x_i is the actual cost; x_i' is the predicted cost; and n is the total number of cases.

It was assessed that the accuracy of construction cost estimation part could be controlled within an acceptable range (the best was +0.38%, and the worst was +32.84%). Mean absolute percentage errors (MAPE) was calculated to be 13.14% which is a good result for a conceptual estimation.

Figure 4. ROI results displayed by VFer

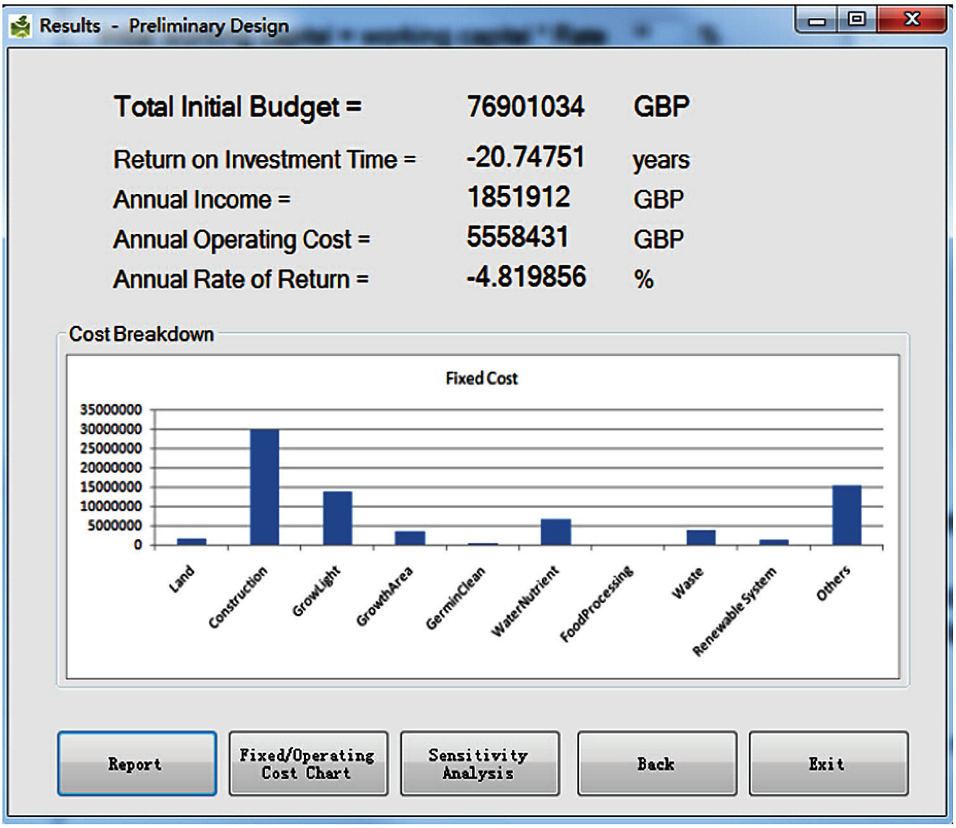


Table 8. Construction cost cross validation with the cost models from Turner & Townsend (2012)

China (Shanghai)			
Cost model	Average Cost (USD/m²)	Predicted Cost (USD/m²)	Error Rate
Office - business park	795	798	+0.38%
Warehouse/factory unit -basic	437	478	+9.38%
High-tech facility/ laboratory	995	886	-10.95%
UK (London)			
Cost model	Average Cost (USD/m²)	Predicted Cost (USD/m²)	Error Rate
Office - business park	2490	2534	+1.77%
Warehouse/factory unit -basic	1328	1664	+25.30%
High-tech facility/ laboratory	2490	2878	+15.58%
US (Washington DC)			
Cost model	Average Cost (USD/m²)	Predicted Cost (USD/m²)	Error Rate
Office - business park	1936	1946	+0.52%
Warehouse/factory unit -basic	883	1173	+32.84%
High-tech facility/ laboratory	1787	2173	+21.60%

System information was taken directly from literature, government databases, or manufacturers' brochures, and this can be controlled within +/-10%. An accuracy of +30% and -20% is expected from VFer as a whole and this level of accuracy is satisfactory, considering a typical range of a conceptual estimation is between +50% and -30% (Phaobunjong, 2002).

THEORETICAL CASE STUDY

Performance of Different Types on Different Locations

The ROI estimations of different types of vertical farm in three selected mega-cities (Shanghai, London and Washington DC) are shown in Figure 5. It is not suggested here that these three cities are necessarily ideal or proposed cities for vertical farm projects, rather they provide worked examples, with readily available data for this research, from three different continents. Applying current average plant prices, it seems that most types of vertical farms will not currently be commercially profitable in these locations. Exceptions can be found in the façade system group. However, since that group has a mixed function including offices then the cultivation area is quite limited, and it is the office rental return that is the contributor of a positive ROI, rather than income from plant production. An exception can also be seen in Washington DC with the artificial growth light types (but only 3.5% return for a bed system, and 3.46% for a drum system).

The budget comparisons for the selected sites are illustrated in Figure 6. Taking London's figures as a standard value '1', a vertical farm project in Shanghai costs less (with an index varies between 0.6 to 0.8). Washington DC has similar values to London, but shows some advantages in single-floor sun-fed types.

Which Plant is More Profitable to Produce?

Income from plant production was simulated to discover the 'profit margins' with the same cultivation system (artificial bed system, in order to eliminate the influence of differences in solar radiation) and the same cultivation area. Comparison results are shown in Figure 7 (taking butter-head lettuce as

Figure 5. ROI of different types of vertical farm growing butter-head lettuce

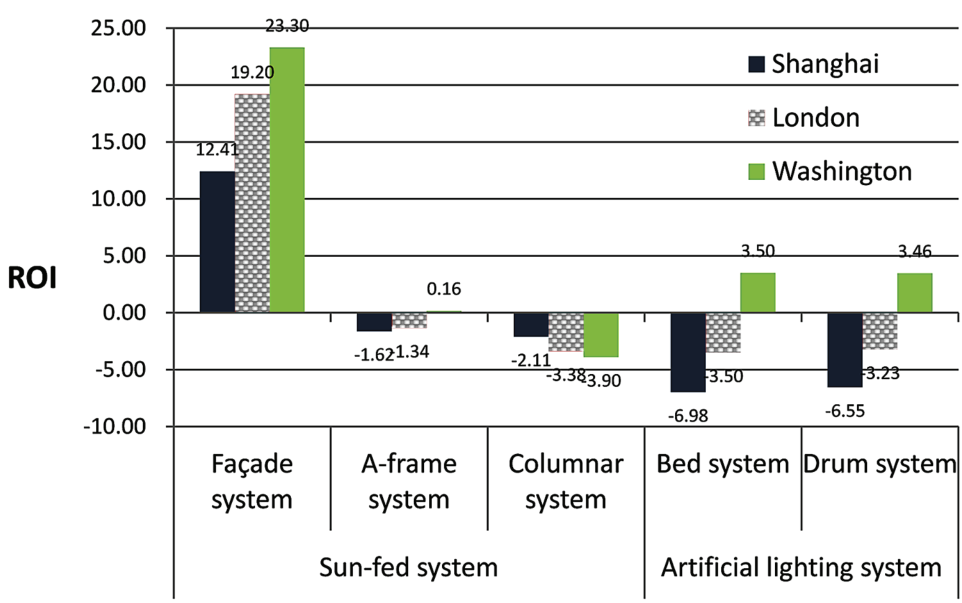


Figure 6. Budget comparisons of different types of vertical farm growing butter-head lettuce

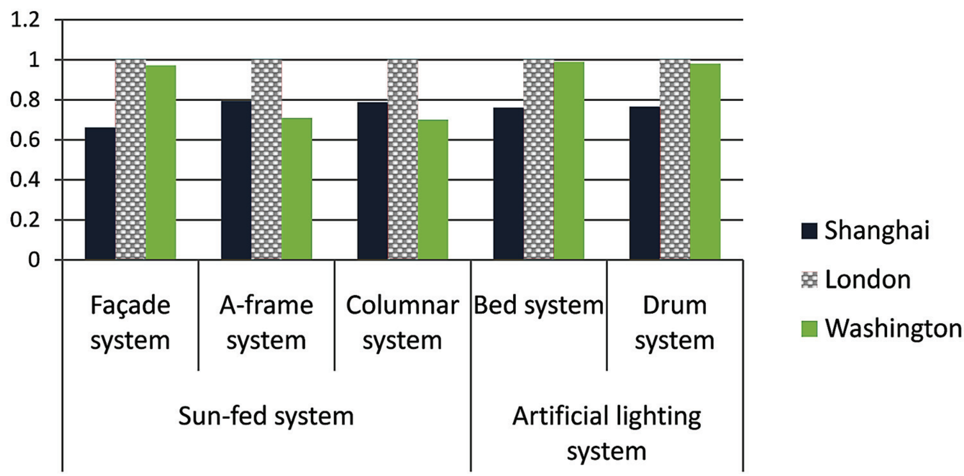
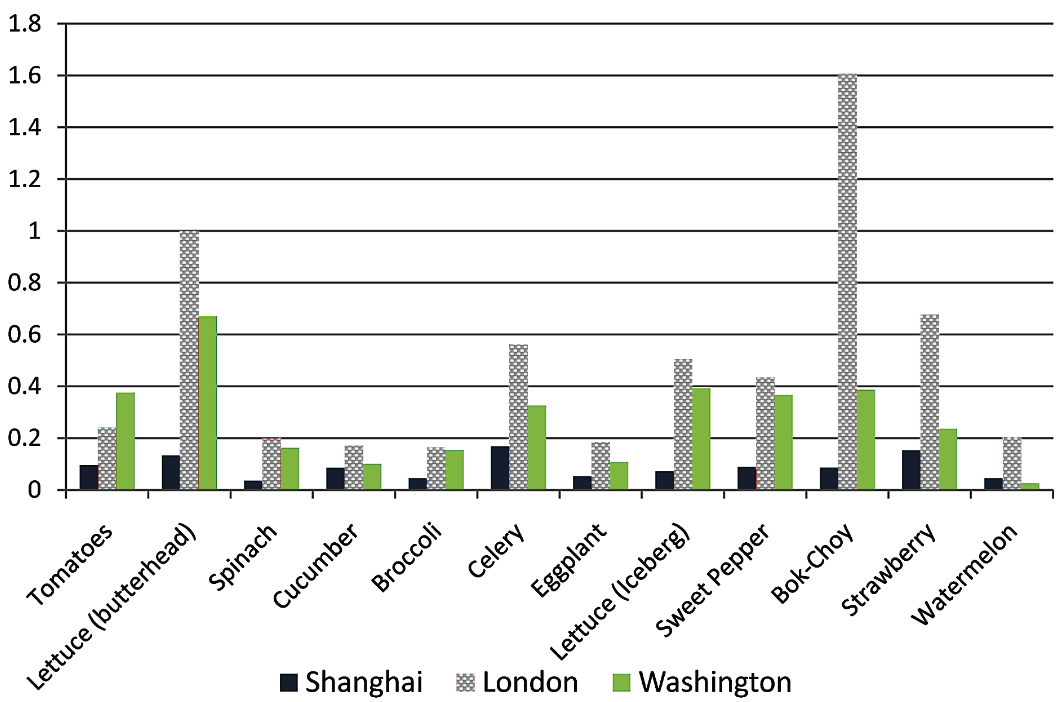
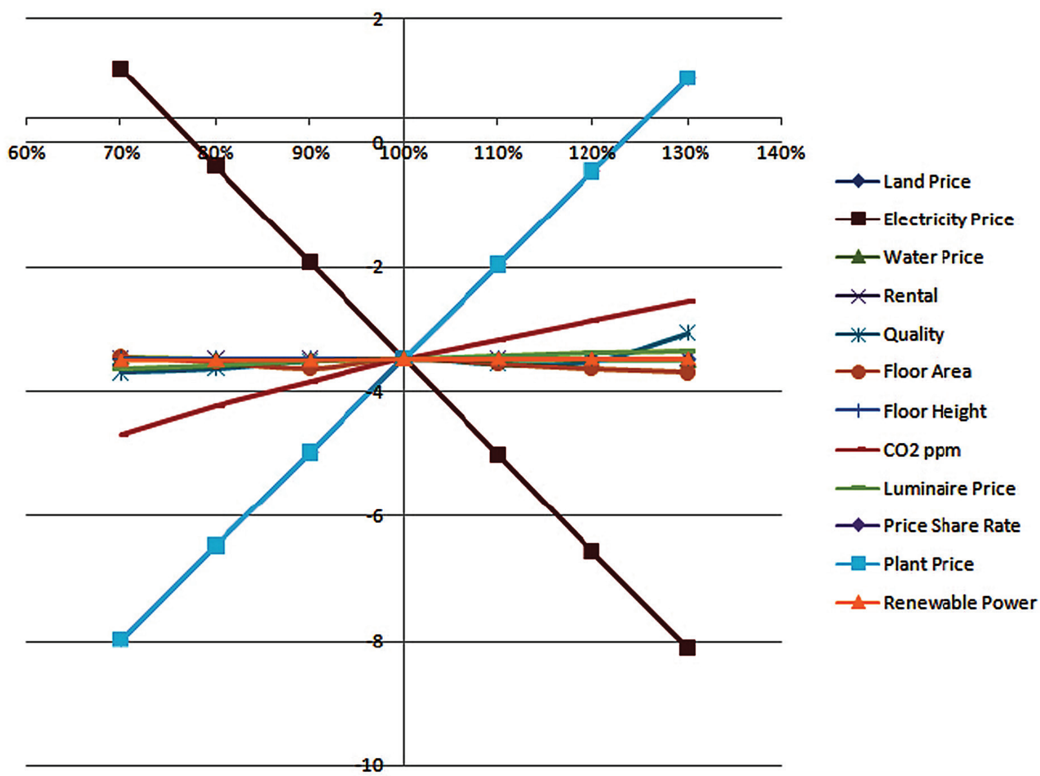


Figure 7. Plant income comparisons



standard value ‘1’). Shanghai has the lowest income according to China’s low price index with celery, strawberries and butter-head lettuce being top three of the list. In London, the most profitable plant should be bok-choy (retail price of 5.6 GBP per kg), which is 1.6 times more profitable than lettuce. However, its supply at present is relatively low and a significant increase in supply could lead to a lower price per kilo. For London, butter-head lettuce and strawberries occupy the second and third places. In Washington DC, butter-head lettuce is top, followed by iceberg lettuce, bok-choy, sweet peppers and tomatoes having similar plant incomes.

Figure 8. ROI sensitivity analysis of an artificial lighting type of vertical farm



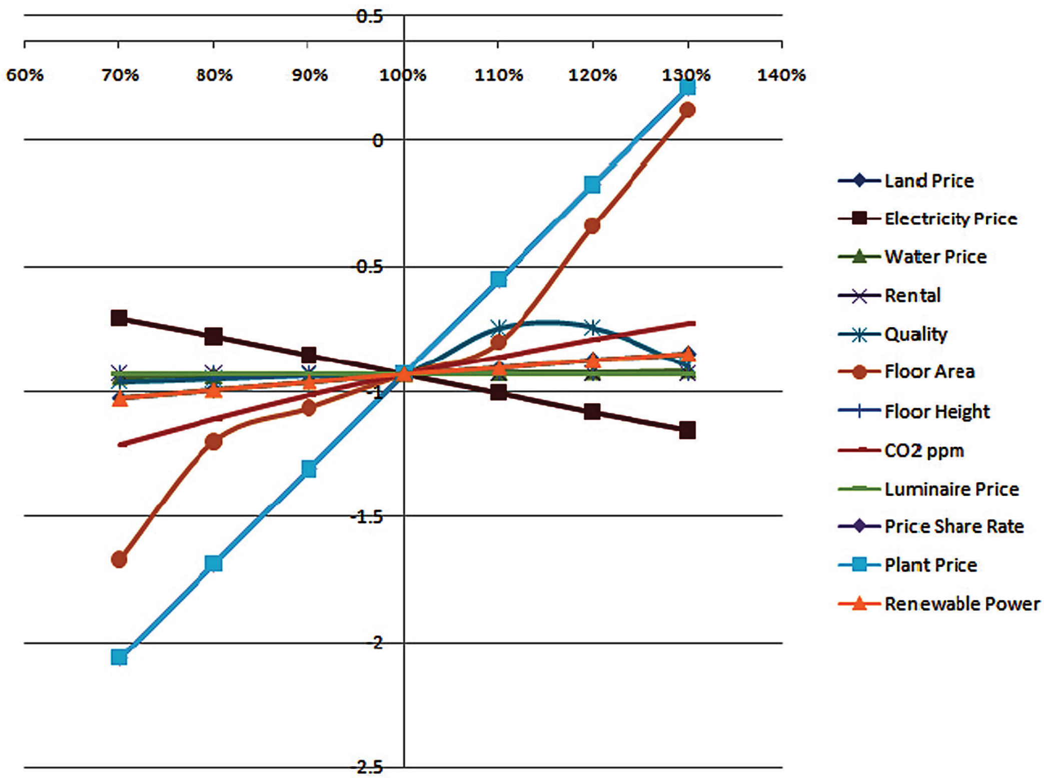
Findings from Sensitivity Analysis

Sensitivity analysis indicates the effects of various factors on the ROI (see Figure 8) and budget (see Figure 9, the larger the slope, the more sensitive a factor is). In terms of ROI, in artificial growth light types, the three most important sensitivity factors are the price of electricity, plant price, and the cost of CO_2 enrichment. In sun-fed types, the three most important sensitivity factors are plant price, floor area, and CO_2 enrichment and electricity price equal. The quality of the building, is also worthy of mention, as this is also quite important in certain circumstances. Significantly, a quality level (including the equipment quality level) 10-15 per cent higher than the medium level, may help to improve the ROI. However, any higher quality is too 'luxurious' for a sun-fed vertical farm since it will reduce the ROI. In terms of budget, for both artificial types and sun-fed types, floor area and quality levels are crucial factors. In artificial types, growth light price is the second in the sensitivity factor list, and therefore needs to be given full attention.

How to Improve the Economic Performance?

The first and most direct way to improve the economic performance of a vertical farm is to set a higher product price. Considering some of the advantages of a vertical farm's produce (fresh, without any pesticides or fertilizers) it is reasonable to set and expect to achieve a higher price than the average market price, as tends to be the case with organically produced foods. Predictions of ROI on changing plant price are shown in Figure 10 (growing butter head lettuce). 'PI' stands for price index and a value of '2' in the PI means the price is doubled, '3' means tripled, and so on. It is clear that although the ROI is negative at current price index (PI=1), it becomes positive value when PI is equal to 2.

Figure 9. ROI sensitivity analysis of a sun-fed type of vertical farm

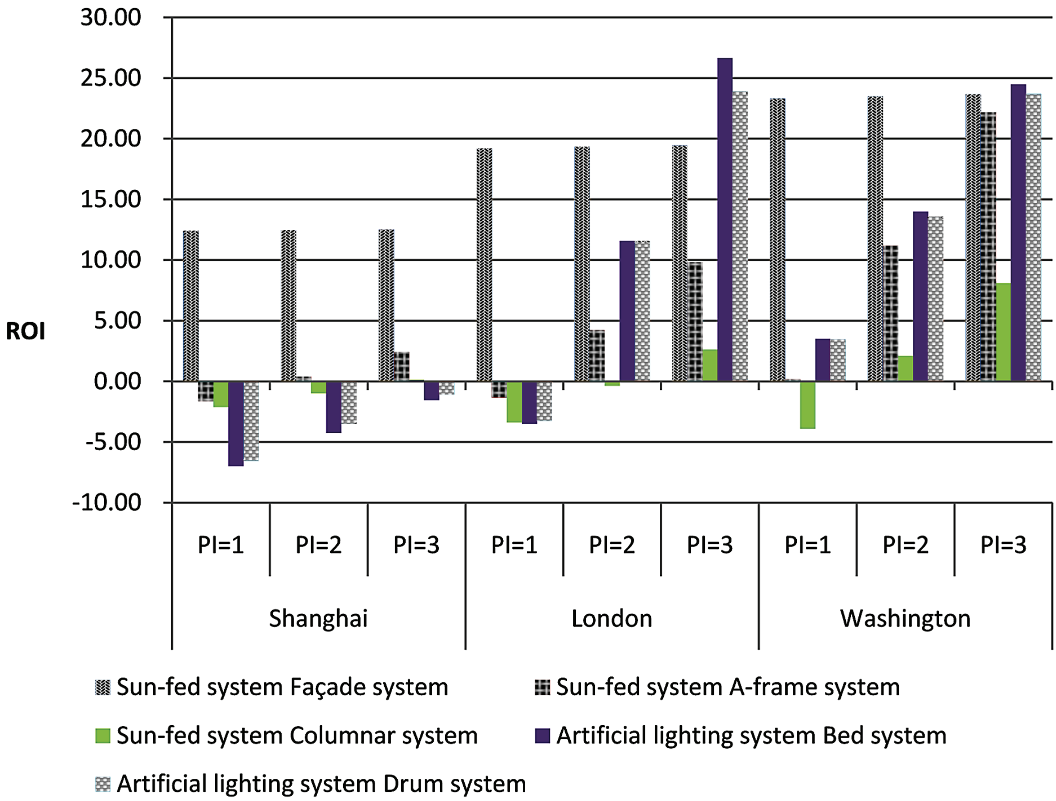


In artificial lighting types, the ROI can then be 12-14 per cent (in London and Washington DC), which already becomes a profitable business that can justify commercial investment. The results show that artificial lighting types of vertical farms show greater potential for ROI growth compared with sun-fed ones. In addition, regional differences are obviously presented. Given the input values in this research, Shanghai does not currently appear to be a good location to develop a vertical farm in comparison to other selected cities.

The second method is to find the optimal strategy, including:

- Selecting the 'right plant' according to the market and cost-effective simulation result from VFer;
- Applying smart ventilation systems and strategies. It was predicted that applying an advanced ventilation system with water spray rather than simply using air-conditioning in an artificial lighting type of vertical farm may effectively reduce the energy consumption for environmental controls, as cooling energy accounts for more than 1/3 energy demand in total;
- 'Think twice' before adding a renewable energy system. Since renewable energy technologies are still costly, they may deteriorate the ROI, although they can reduce the project's carbon footprint. Nevertheless, certain kinds of renewable energy system may be more suitable for particular sites. However, it is recommended to apply them after a full evaluation on their cost-effective performance is made;
- Applying supplemental growth light to sun-fed vertical farms in order to stabilize the photosynthetically active radiation (PAR) on the plants' canopies and thus to improve the yields.

Figure 10. ROI comparisons with different price indeces (PI)



Thirdly, the ROI can also be improved through advances in scientific development or as a result of evolution in technology. For example, testing the hypothesis that smaller plant spacing in a bed tray may benefit the efficiency use of light, thus improving the yields, can be of great research interest in vertical farming. Besides, every new generation of growth light, either LED or other advanced sources, is continually changing the balance sheet. As a result, with time higher efficiencies are expected, and therefore a more attractive ROI is likely to be achieved.

Last but not least, financial support or subsidy from government, for example, could be a catalyst that enables more pioneering projects to be developed. In some countries or cities, direct support could become a priority as part of planning regulations, completed infrastructure, supplementary allowance and so forth. In addition, indirect support could include the development of industry standards to regulate the market, certificating products from a vertical farm to acknowledge the high quality, and propagating the vertical farming concept to build a more knowledgeable environment which in turn will give more confidence to developers and investors (Heath & Shao, 2014).

CONCLUSION

VFer provides an innovative and highly flexible, customised system to estimate a vertical farm's cost and performance. In this research, the results from several typical configurations were used to elucidate the economics of vertical farms. With respect to the sun-fed type of vertical farms, under current average plant price levels, they appear to barely break even in terms of financial return. Indeed, their economic performance largely relies on the availability of solar radiation and other external factors. Since they are actually variants of a single-floor vertical farm (assuming the façade system as a "vertically designed" single floor farm, which is quite shallow in depth), the scale and production are inevitably constrained. However, in some specific locations, where there is plenty of natural light available, the plant price is relatively high, and there are physical or fertile land resource constraints, such as Singapore or Middle East countries, this could be a viable system.

In terms of the artificial lighting type, estimates show that the ROI varies from case to case, but all are negative with current technology and current average food prices. However, this trend is likely to change within 3 to 5 years if the efficiency of LEDs or the price of products produced in a vertical farm can be doubled (similar to the trend for the price of organic produce). In such a scenario, the ROI can be 12 to14 per cent, and this does not include the extra profit of potentially selling the land saved from by adopting vertical agriculture. Therefore, although pure artificial-energy-driven farms may be not so optimistic at present, they could still be a viable alternative agricultural solution in the near future, in particular locations, especially as food security is becoming an increasingly global concern.

The next important step for research into vertical farming is to work with the existing small-scale pioneers of urban agriculture and vertical farm projects to develop and refine increasingly accurate cost models. This in turn will enable more informed decisions on the part of developers, investors and local governments and should in turn lead to the establishment of this new urban building and land-use typology.

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Yiming Shao is an architect and researcher in sustainable building design, simulation and modeling of indoor and outdoor built environment. His research interest encompasses the design and estimation of the vertical farm. Tim Heath is the Chair of Architecture & Urban Design at the University of Nottingham. He is a registered architect, qualified town planner and experienced urban designer who is actively engaged in research, teaching and practice. Having joined the University of Nottingham as an academic in 1993, he was previously Director of Architecture, Head of the School of the Built Environment and subsequently the Department of Architecture & Built Environment. He has also been the Associate Dean for Intenrationalisation and External Relations in the Faculty of Engineering and Acting Vice Provost for Research & Knowledge Exchange at the University of Nottingham Ningbo China. Professor Heath's research interests are broad and span architecture and urban design. As an academic he has published extensively with many books, chapters, journal papers and presented at major international conferences in the areas of urban design, conservation, adaptive re-use of buildings, elderly housing, vertical farming, sustainable cities and eco-urbanism. He also has a large PhD group undertaking research projects that focus on various aspects of these topics and together with these research students plays a key role in the Energy & Sustainability Research Division' and the Environmental Physics and Design Research Group. Significant recent publications include the completely revised second edition of the Public Places Urban Spaces (2010) book published by Architectural Press of which the first edition sold over 10,000 copies in English and was also published in Chinese, Arabic and Korean. Professor Heath has extensive experience as an academic and practitioner in Asia and particularly in China. In August 2010, he also organised the high-profile international symposium 'Eco-Urbanism: towards sustainable living' at the EXPO 2010 in Shanghai. This event involved several prominent academics from across Europe, US and China including MIT, Tsinghua, Tongji, Nanjing, Tianjin, South-East, and Hefei universities. He also led a successful joint postgraduate architecture and urban design studio projects with Tsinghua University and Tianjin University and has delivered invited lectures at many Chinese universities. He has also been a visiting professor at the Chinese Academy of Sciences in Beijing. Professor Heath has acted as an external examiner for undergraduate, postgraduate and PhD programmes at universities in the UK and internationally. His current research interests are in the areas of architecture design, places and cities, conservation and regeneration, adaptive re-use, vertical farms, and elderly housing.

Yan Zhu is an Assistant Professor in Architecture and Urban Design, at the Department of Architecture & Built Environment, University of Nottingham. His research area is sustainable urban design and regeneration, both from an environmental and social perspective. He graduated with a BArch degree from the School of Architecture, Tsinghua University in China and obtained his Master's degree in Architecture and Urban Design and PhD from the University of Nottingham. Dr. Zhu previously worked as an Architect and Urban Designer. Yan has practical experience from a series of projects in urban design, urban regeneration and urban environmental performance assessment.

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