A COMPREHENSIVE ECONOMIC ANALYSIS OF VERTICAL FARMING: QUANTITATIVE MODEL AND A DECISION SUPPORT SYSTEM FOR THE COMPETITIVE MARKETPLACE

by

Faraz Moghimi, B.S.

A thesis submitted to the Graduate Council of
Texas State University in partial fulfillment
of the requirements for the degree of
Master of Science
with a Major in Engineering
August 2020

Committee Members:

Bahram Asiabanpour, Co-Chair

Hamed Ghoddusi, Co-Chair

Harold Stern

COPYRIGHT

by

Faraz Moghimi

2020

FAIR USE AND AUTHOR'S PERMISSION STATEMENT

Fair Use

This work is protected by the Copyright Laws of the United States (Public Law 94-553, section 107). Consistent with fair use as defined in the Copyright Laws, brief quotations from this material are allowed with proper acknowledgement. Use of this material for financial gain without the author's express written permission is not allowed.

Duplication Permission

As the copyright holder of this work I, Faraz Moghimi, authorize duplication of this work, in whole or in part, for educational or scholarly purposes only

ACKOWLEDFEMENTS

Special Thanks to both my co-advisors and mentors Dr. Asiabanpour, and Dr. Ghoddusi, who have supported me through all of my research endeavors during the past couple of years. I should also note my deep appreciation to Dr. Asiabanpour who have greatly helped ease my transition to the life here at Texas State University. My gratitude goes to Dr. Stern as well for his role in my thesis committee.

TABLE OF CONTENTS

Page

LIST OF TABLES

Table **Page**

LIST OF FIGURES

Figure **Page**

LIST OF EQUATIONS

Equation **Page**

ABSTRACT

There are various problems associated with our conventional practice of farming. In the past few years alone, agriculture has been responsible for a million square kilometers of deforestation. The world is facing a water crisis, and farming is responsible for using 80% of its freshwater. Also, the prospect of global climate change is projecting a much riskier future to practices of conventional farming due to more pesticide incidences, weather uncertainties, changing rain patterns, and more frequent climate extremes. One could argue that these alarming problems might someday be treated as more imminent as the population grows, less fertile land becomes available, and the effects of global climate change become more apparent. Vertical farming solves a lot of the discussed issues associated with traditional farming by using considerably less water, requiring less land, and not relying on the environmental conditions whatsoever. These are all excellent features, but vertical farming is also energy and labor intensive and can be quite expensive in some cases. This study worked to quantitatively model and evaluate the economic prospect of pursuing vertical farming as a business venture in a competitive marketplace under different circumstances. This effort is deeply needed by both the scholarly field and the young industry. This project initially develops a comprehensive stochastic theoretical model to evaluate vertical farming with respect to traditional farming in various conditions. This comprehensive theoretical model is then revised to match the real-world data. The revised model is then utilized to develop a Decision Support System that could help identify the best competitive location alternative to pursue vertical farming as a business practice. The

system would account for both profit and risk decision factors as well as stakeholder preferences. Moreover, the developed Decision Support System is employed for a case study to locate the best location alternatives for implementing vertical farming in the US by considering the relative profit potentials and risks in each region. The results from the system identify the most suitable locations to pursue vertical farming as a business venture. These results also contribute towards forming a better understanding of current and future states of the vertical farming industry.

1 INTRODUCTION

1.1 Problems with our Current State of Agriculture

Agriculture was one of the key aspects of the development of human civilization early on. Around 12,000 years ago, our ancestors abandoned the hunter-gatherer lifestyle and triggered the "Neolithic Revolution" by swathing to agriculture and permanent settlement (Geography, 2018). To this day, sustainable and well-functioning agriculture remains an essential part of any modern and prosperous society.

Although agriculture is a necessary part of preserving human life, agriculture and activities associated with it have been known to have a variety of harmful environmental impacts (worldatlas, 2018). More findings during recent years are unraveling the extent of the damages the growing agriculture industry has on our environment. Climate change and agriculture are closely interrelated. Climate change has negative influences on agriculture in various ways, including rising temperatures, changing rainfall patterns, climate extremes, and pesticides/disease patterns. On the other hand, agriculture contributes to the global climate change by producing approximately 25% of the man-made greenhouse gases (Smith, 2014), and possible deforestation (Milius, 2017). In addition, the massive supply chain industry surrounding agriculture accounts for a good deal of CO2 emissions created as well. Some of the other environmental impacts associated with agriculture are soil degradation, deforestation, irrigation, and pollution, each causing several environmental hazards. Irrigation currently uses up to 80% of our freshwater (Govrenment, n.d.). We should bear in mind that according to United Nation’s 2018 water development report (Houngbo, 2018), more than two billion people lack access to safe drinking water. In addition, the population growth, creation of new industries, and economic expansions resulted in a consistent 1% yearly increase in the demand for clean water over the past 10 years. This increase in demand will continue to grow by 33% by the year 2050. Hence managing our clean water resources better should be one of our priorities. Finding a way to reduce water consumption by the agriculture industry, the largest freshwater consumer can be a good way to start.

In addition to environmental problems, traditional farming practices have a sustainability problem as well. Agriculture is resource-intensive. It requires a lot of lands and water. With the growing increase in the world population and food per capita consumption, it is getting more difficult to sustain traditional farming production. Moreover, farming is generally heavily reliant on the environment, but due to global warming, rainfall and pesticide patterns are changing, and weather extremes are becoming more frequent. Overall, one can see that exploring new methods of sustainable agriculture, while reducing its environmental impact, and minimizing its water usage can be of great importance to our future food, water, and environmental safety.

There are a variety of estimations on the global value of the agriculture and farming industry. It can be confusing to estimate the exact value given the industry is interconnected with different kinds of food services. According to the FAO, the food and agriculture sector accounts for approximately 10% of the aggregate global GDP (FAO, n.d.). That would put the current agriculture industry value somewhere above $2 trillion. These numbers are only going to increase by the year 2050 due to the inevitable population growth. The large scale of this industry makes a good case for innovation from a range of angles. However, we should have in mind that the profit margins per unit in this industry are generally slim.

Moreover, every produced product usually has a short expiration date, and it cannot be sold after that point. Hence, efficient supply chain management and inventory management is a vital part of any agricultural businesses. Hence, innovations in this sector must emphasize the logistics and inventory. One can see that well developed and marketed agriculture alternatives might prove quite appealing financially even if they successfully participate in only a small part of this vast market.

1.2 What is Vertical Farming?

There have been a variety of new technologies looking to reduce the harmful environmental effects of agriculture while proposing novel potentially profitable methods of farming. Different types of vertical farming are of these new methods. Vertical farming is a method of growing plants without soil by using a mixture of water and the required minerals in a controlled environment (dos Santos, 2013). The most common products generally produced by vertical farming systems are lettuce, tomato, basil, cucumber, flowers, and marijuana, in either shipping container environments (Freight Farms, 2020) or large-scale warehouses (Aerofarms, 2020). In the following segments, some of the relevant technologies associated with vertical farming are briefly discussed.

Figure 1. Vertical farming in practice

1.2.1 Hydroponics

Hydroponics farming is one of the main technologies associated with vertical farming. Hydroponics is a soilless practice of growing crops in a medium of liquid and nutrients. This medium varies depending on the product; however, it typically includes water and organic nutrients like nitrogen, phosphorus, sulfur, etc. (fullbloomgreenhouse, 2019)

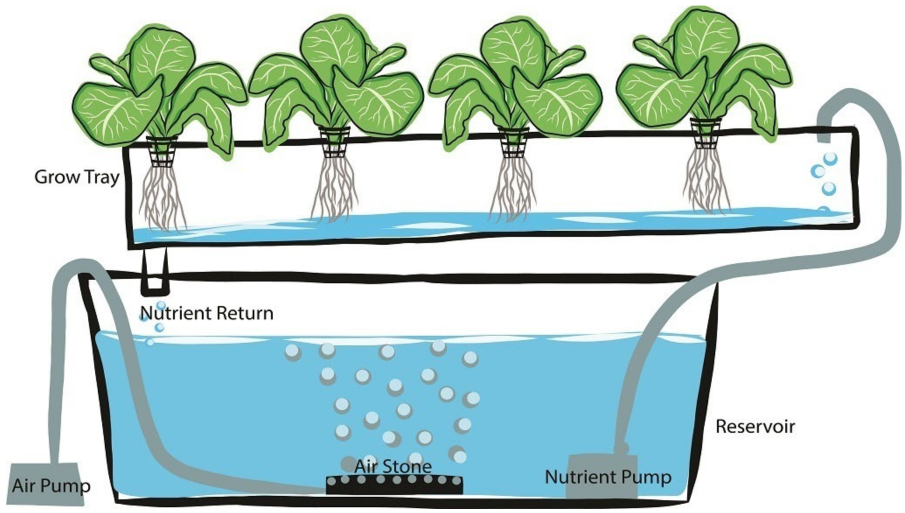

Figure 2. A general overview of simple hydroponics system in which the water and required minerals are added to a water bed and pumped to medium for crop growth.

1.2.2 Aquaponics

Similar to hydroponic systems, Aquaponics grow crops by using a medium of liquids and nutrients. However, aquaponics systems take this design one step further to raise fish simultaneously with the crop. Aquaponics systems use the nutrient-rich water of the fish tanks as the medium to grow crops (James E. Rakocy, 2013). Even though Aquaponics, as a concept, provides a fascinating efficient idea, due to the aquacultural practices of aquaponics they are rarely used in commercial implementations of vertical farming, which usually solely focus on producing crops.

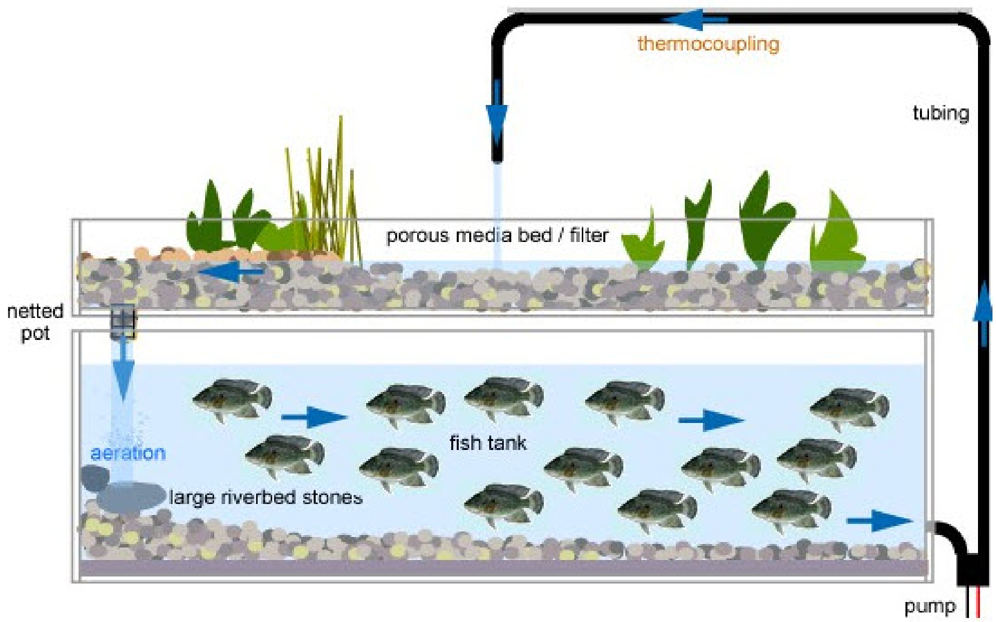

Figure 3. An overview of an aquaponics system in which the necessary minerals are derived from the fish tank to support plant growth.

1.2.3 Aeroponics

Unlike hydroponics or aquaponics, aeroponic system nourish plants without a liquid medium using nothing but nutrient- charged mist (Figure 4). In this method, plants are grown in a controlled environment in fixed frames and the necessary minerals and moistures are sprayed on them. (James Clawson, 1998) Consequently, aeroponic farming requires less water and nutrient compared to hydroponics and aquaponics.

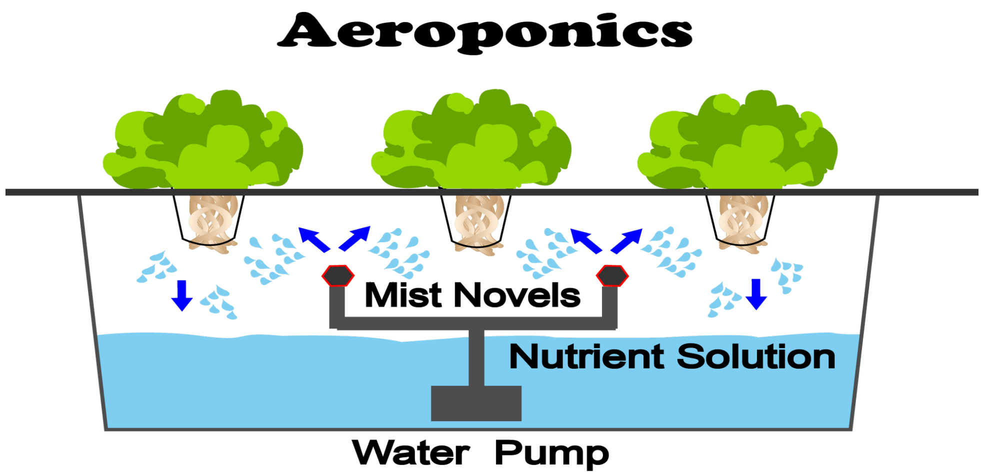

Figure 4. A general overview of an aeroponics system where minerals and moisture are delivered to plants in a fixed frame.

Each of these vertical farming techniques can be implemented in various ways on their own or in a hybrid setting. In this project, we examine Vertical Farming in hydroponics or aeroponics settings as they are known to be more of a commercially viable practice. Aquaponics systems will not be the subject of this study due to their impracticality and unnecessary complexity. Also, it should be noted that since the large warehouse practice of vertical farming (factory farming) is the largest scale of vertical farming that has been implemented in the industry, it will be considered as the benchmark form of practice in this study.

1.3 Vertical Farming: A Possible Solution?

Vertical farming presents numerous advantages as it does not require any soil. So, it can be implemented anywhere, which means farming in non-prolific land, limited spaces, and cutting down the transportation costs and cost factors associated with land care. This means that there would be no deforestation and desertification effects related to this method of farming. Moreover, vertical farming's procedures and efficiency are independent of its surrounding climate. Therefore, global warming and climate volatility, in general, would have no impact on its performance. That also means more reliable production predictions and reduced storing costs. To add on, vertical farming has a much smaller carbon footprint compared to traditional methods of agriculture. Another advantage of vertical farming is its frugal water consumption. For instance, hydroponics farming, the most known method of vertical farming, generally consumes 90% less water to deliver crops than traditional agriculture (Service, n.d.). Fewer pests and diseases, better growth rate, and efficient use of nutrients are other advantages of vertical farming. However, vertical farming has a wide range of problems as well.

Most vertical farming ventures in today's world are pretty small in scale compared to other types of agriculture. As a result, the technology has not reached its most efficient state. Vertical farming can be energy and labor-intensive. This makes it hard for its products to compete with regular agriculture, which benefits from better cost efficiency due to large scales and many years of optimization. Hence, the feasibility of implementing vertical farming systems can be quite volatile, depending on several factors. For instance, if we establish a small-sized hydroponic system right next to a large-scale automated tomato farm during the tomato season, we will probably not be able to compete with the farm. However, if we put that same hydroponic container in a populated area, perhaps a place with uncultivable land, shortage of rainfall, volatile weather conditions, expensive water rates, low energy rates, and expensive land in a period that is not tomato season, we actually might be able to compete with the regular tomato farmers. What are the other factors influencing hydroponic systems' performance? What is its impact? Is there a way to implement vertical farming systems that is prolific and financially promising? If so, what is it? These are interesting concepts that are worth exploring. As a part of this thesis, we aim to help answer some of these questions and more and pave the way for identifying the best and most efficient course of action for implementations and investments in vertical farming systems.

1.4 Research Proposition

This study aims to model vertical farming performance and economic prospect with respect to traditional agriculture under different circumstances. Chapter 2 proposes a comprehensive stochastic model that evaluates vertical farming with respect to traditional farming in different seasons, products, scales, and locations. Chapter 3 works to revise the initial model to make it implementable and practical, making the model compatible with the real world information. Chapter 4 utilizes the quantitative model to develop a Decision Support System that would help stakeholders choose the best location alternative for implementing vertical farming from wide a range candidates. Chapter 5 employs the Decision Support System to conduct a case study regarding the economic prospect of applying vertical farming within the US, in a competitive market setting. Chapter 5 uses the generated results to provide some insight into the current and future states of the vertical farming industry. These results also contribute a great deal towards forming a better understanding of the current state and the future of vertical farming industry.

1.5 Research Questions

The main research questions asked and answered by this study are listed as follows:

- ✓ What are the quantifiable competitive advantages and flaws of vertical farming with respect to field-grown agriculture? (Chapter 2)

- ✓ How can we mathematically model the economic prospect of vertical farming with respect to traditional farming? (Chapter 2, Chapter 3)
- ✓ How can we revise a quantitative model to be practical and compatible with the current lack of data in the vertical farming industry? (Chapter 3)
- ✓ How can we develop a model that identifies the best locations for pursuing vertical farming? (Chapter 3)
- ✓ How can we design and develop a Decision Support System that could identify the best location alternative for implementing vertical farming among a set of candidate alternatives? (Chapter 4)
- ✓ What is best the best location alternative to implement a vertical farming business within the US? (Chapter 5)
- ✓ What are the characteristics of the best location alternative for implementing vertical farming? (Chapter 5)
- ✓ Does vertical farming have a profit margin advantage in any location? (Chapter 5)
- ✓ What does the future look like for vertical farming and what industry trends would help contribute towards a favorable prospect for the young industry? (Chapter 5)

1.6 Significance of Research

Vertical farming is a relatively new industry, and it might play a huge role in helping establish the future of our food sustainability and helping save the environment. However, there has been limited scholarly research on vertical farming, and of those, almost all focus on the technology and agricultural aspect of vertical farming. A minimal number of publications choose to investigate the economics and business prospect of vertical farming. Like any other emerging technology, financial incentives must exist so that an industry can flourish. Thus, there is a critical need for more fresh perspectives to analyze vertical farming from an optimization and business point of view. To the best of our knowledge, there have been no prior literature attempts to develop models and systems that evaluate vertical farming with respect to traditional agriculture under different conditions and locations to find the best locations to pursue vertical farming in a competitive marketplace. In addition, this study proposes one of the first Decision Support Systems developed specifically for vertical farming business decisions. Also, to the best of our knowledge this is the first time a case study on this scale has been conducted to evaluate vertical farming from an economic decision making perspective.

1.7 Literature Review

1.7.1 The Technology Aspect

The majority of the research in this field focuses on the technology and design aspects. There is a large body of literature focusing on the technology aspect of vertical farming, but due to its irrelevance to the focus of this study, only a few examples are reviewed here. Vertical farming is a general concept, and there are a few specific and comprehensive designs for vertical farming in the literature (Fischetti, 2008) and (US Patent No. 10,306,847, 2019). (Coleman, 2014) describes the development of small scale low tech vertical farming for their application in Nairobi and Kenya. (Fatemeh Kalantari1, 2017) examine different technologies associated with vertical farming and their overall impact on the performance. This includes technology features like lighting, solar, water recycling, along with a review of different types of vertical farming methods like hydroponics and aquaponics, etc. (McAinsh, 2016) analyses vertical farming systems from growing space efficiency and assesses the possible impact utilizing artificial lighting in vertical farming systems. (Molin, 2019) works on assessing the sustainability and environmental impact of a hydroponics system in Sweden. (Choez, Cortázar, Cruz, & Carvache, 2017) works on developing a framework Pest analysis tool applied to a vertical farming case study. (Fatemeh Kalantari, 2017) reviews a generalized survey's responses and discusses the pros and cons of vertical farming.

1.7.2 Qualitative Economic Perspective

Some researchers focus on addressing the generalized aspect of vertical farming in terms of overall pros and cons. These include subjects like vertical farming's social prospect, place of vertical farming in the future agriculture industry trends, and prospects for implementing vertical farming systems. (Cıceklı & Barlas, 2014) explore the concept of replacing greenhouse farming structures with vertical farming systems in big metropolitan areas. (Besthorn, 2012) focuses on assessing the qualitative potentials of Vertical Farming from a Social Studies perspective, not entirely relevant to our subject of study, but an interesting subject of study, nonetheless. (Andrew M. Beacham, 2019) discuss some of the advantages and disadvantages of vertical farming and the issues surrounding its implementation, mostly from a qualitative point of view. (Anirudh Garg, 2014) discusses the fact that given the current state of agriculture, the rise of more innovative and sustainable approaches is inevitable. He then evaluates vertical farming and organic food's place in this trend in a mostly qualitative manner. (Tomkins, 2017) reviews the current state of vertical farming practices and cites mostly qualitative advantages and disadvantages of vertical farming.

Generally speaking, the pros and cons of vertical farming are commonly known in the literature. The quantitative impact and relation of those pros and cons are what forms the questions of this study. Also, possible social, educational, etc. contributions of vertical farming are not the subject of this study. Hence, we would suffice to the cited articles

1.7.3 Quantitative Economic/ Business Perspective

Only a few scholarly projects in this field look to analyze vertical farming quantitatively and evaluate its feasibility and economics. (MalekAl-Chalabi, 2015) first defines and selects a specific vertical farming design. Then the study goes on to model the area, water, light, energy, and solar panels required for vertical farming to evaluate whether solar panels can be used to power vertical farming. (Chirantan Banerjee, 2014) provides one of the few detailed economic analysis done in this field. It provides estimations regarding energy use, workforce, production, and costs, etc. It then explores some of the general market potentials of vertical farming in different regions. The (Toyoka Kozai, 2020) books takes a deep dive into different aspects of factory farming and review different technologies and the current state of the industry in different continents. (TRIMBO, 2019) examines the economic suitability of vertical farming in Sao Paulo by estimating the costs of vertical farming in a context of a case study. There are a number other case studies assessing whether vertical farming could break a profit under certain conditions which typically include special case cost estimations and possible NPV or other profit indexes (Sulma Vanessa Souzaa, 2019), (D. Leite, 2016). (de França Xavier, 2018) conducts another case study analyzing the impact of different effluents on the case study's profit index. While these few studies contribute to the research field by providing a better understanding of vertical farming's cost structures along with insights to special case implementation of vertical farming, there are very important factors usually missing in the mentioned case studies. It is often forgotten that vertical farming must operate in a competitive marketplace where it has to compete with conventional farming. Analyzing vertical farming without considering conventional agriculture can appear incomplete. Also, most of models used in the reviewed literature are ad hoc models dedicated only to that case study. In other words, not applicable to general use. Moreover, most of the mentioned studies fail to take into account the risk aversion advantages of vertical farming altogether. In addition, most of the literature in the field assesses vertical farming in a micro scale. The few studies examining vertical farming on macro level typically use qualitative methods.

As one can see, there is a dire need for more research to comprehensively analyze the performance and economics of vertical farming quantitatively. (1) To the best of our knowledge, there are no research publications proposing a comprehensive performance and fiscal model for vertical farming on a macro level (both stochastic, and deterministic) (2) that can be applied to a variety of cases. (3) Moreover, this study takes into considered every analysis in a competitive market setting, where vertical farming is evaluated with respect to conventional farming.(4) Also, this is perhaps the first time that the risk aversion aspect of vertical farming is taken into account in a quantitative model. (5) Also, to the best of our knowledge this study proposes the first Decision Support System specifically designed for assessing vertical farming alternative locations. (6) In addition, we have not come across any case studies that would assess vertical farming's economic prospect within the US in a scale that will be conducted in this study.

2 COMPREHENSIVE STOCHASTIC MODEL

This chapter proposes a theoretical modeling framework for financial analysis of vertical farming with respect to traditional agriculture. This framework includes defining the relevant static and stochastic states and parameters, identifying the relation among defined parameters, formulating a financial prospect indicator model, and proposing a stochastic model that can be used to identify the most profitable, least risky, and least environmentally hazardous states of vertical farming implementation.

2.1 Parameters and Relations

2.1.1 The main states

The first step in formulating this framework is to define the states in which the parameters are defined. *Start Season*, *Location*, *Scale* and *Product Type* are the four state variables as follows:

Start Season (s): In the scope of this modeling practice, the concept of time has been simplified using seasons as a discrete-time series. The season state brings the stochastic nature to this framework as the parameter estimations in any state in the future season can be modeled as a stochastic process. The season would manifest itself as s (start season), s+n (end season), and j (season in progress) in which n represents an investment time period chosen by the investor.

Location (l): Parameters' value would differ from region to region. For instance, tax rates, weather conditions, energy prices, and land prices in the city of Austin are different from those in Los Angeles. The location is a non-numerical label representing the metropolitan area and its surroundings.

Scale (k): In every investment and business venture, the scale matters, and this case is no different. In this formulation, average seasonal production measured in weight is assigned as the value of the Scale state.

Product Type (p): The last state condition takes into account the product type. The value of this state variable is non-numerical and can be any of the produced crops by vertical farming systems like "lettuce," "basil," "tomato," etc.

Having identified the states within the scope of this study, it should be noted that every static and stochastic variable from this point forward must be a function of these defined states.

2.1.2 Profit

Profit estimations and expected cost and income are essential to economic analysis. First, it should be noted that profit is a relative function of *income*, *cost*, and *tax*:

$$Profit = f\,(income,\ cost,\ tax)$$

$$Cost = f(\ Initial\ Investment,\ Labor\ Cost,\ Energy\ Cost,\ Water\ Cost,\ Material\ Cost,\ Transportation\ Cost,\ Maintaining\ Equipment\ Cost,\ Insurance\ Cost)$$

$$Income = f\,(\ Sales,\ Market\ Prince)$$

Equation 1 Income relations

2.1.3 Risk

There are five types of risk in the farming business. These are production risk, price or market risk, financial risk, institutional risk, and human or personal risk (Economic Research Service, 2019). These risk categories respectively refer to uncertainties about the natural growth process of crops (weather, disease, pest, etc.), volatile prices, debt payment and interest rates, uncertain governmental actions that affect the business, and human health or personal problems. Any accurate risk indicator must be a function of these five risk categories:

$$Farming\ Risk = f\ (production\ risk,\ price\ or\ market\ risk,\ financial\ risk,\ institutional\ risk,\ human\ or\ personal\ risk)$$

Equation 2. Farming risk relations

In this study, the goal is to formulate an evaluation for vertical farming with respect to tradition agriculture practices. Also, it is assumed that the financial risk, institutional risk, and human or personal risk would be the same for both practices. Hence, this study would only take into account production risk for each method as well as a singular stochastic price risk for both models.

$$Simplified\ Farming\ Risk = f\ (production\ risk,\ price\ risk)$$

Equation 3 Simplified farming risk relation

Moreover, as risk estimation in the farming business is a complex topic in reality, one could look at insurance estimations as an alternative approach to indicate risk if the direct method proves too complex or impractical. In other words if it is assumed that the insurance rate estimates provide a good enough representation of the expected risks associated with farming. That said, one should also consider the fact that although the insurance estimations can be quite accurate and well tested for traditional farming, it much more of new subject when it comes to vertical farming. Thus it may be susceptible to error for that form of practice.

$$E\ (Simplified\ Farming\ Risk) \sim Insurance\ Rate$$

Equation 4 Expected simplified risk

2.1.4 Environmental Hazard

The framework should take into account the major environmental hazard factors associated with farming to evaluate the environmental hazards in vertical farming systems relatively. Different aspects of farming's environmental harm are greenhouse gas emission, deforestation, waste production, and irrigation harm.

$$Environmental\ Hazard = f(\ greenhouse\ gas\ emission,\ deforestation,\ waste,\ irrigation)$$

Equation 5. Environmental hazard relations

2.2 Model Formulation

2.2.1 The Relative Concept

The first important step is to take into account the relativity concept. As discussed before, analyzing vertical farming is an alternative to traditional farming, the dominant practice in the market. Thus, the *relative* function is defined as follows:

$$Relative\ (function) = Vertical\ Farming\ Function_{slkp} - Traditional\ Farming\ Function_{slkp}$$

Equation 6. Relative function

2.2.2 The Concept of Time

Seasonal averages are considered as the time frame in which all of the variables and functions are measured. Hence, all of the variable used in the model must be converted to seasonal averages. In this study, it is assumed that n is the number of seasons that an investor wants to be involved with the project. For instance an investor might look for a year or 10 years of investment in vertical farming for which the n is 4 and 40 respectively. Therefore, every type of quantitative variable that is not in the form of seasonal measurement must be converted into seasonal variables. For instance, the initial costs must be converted to seasonal annuities.

$$\textit{Initial cost annuity} = \textit{Initial investment } (A/P, MARR, n)$$

Equation 7. Where MARR is the minimum attractive rate of return for a particular investor, and n is the number seasons the project is expected to run.

2.2.3 Expected Profit Formulation

One of the main decision factors in every investment decision is the expected profit of that particular investment. Have in mind that variables influencing the value of expected profit, such as *market prices*, *demand*, *sales*, *water price,* and *energy price*, are stochastic processes. Therefore, if the proposed model is to be used in a decision making context that takes into account future events, the profit is a stochastic process. The probability functions of several contexts/ processes can be obtained from the relevant and suitable stochastic processes and past empirical data. Here, it is assumed that Profit is a discrete-event stochastic process where {Profit (i) = Xi = k, i ≥0, k=0,1,2,3, ... , m} and Pi= P{Profit(i)

= Xi = k, i ≥0, k=0,1,2,3, ... ,m}where Profit(i) is a particular discrete scenario that can happen in the future, and Pi is the probability of that even happening. Thus, the expected profit for a single season is:

$$E\ (Profit\ (s,l,k,p)) = \sum_{i=0}^{i=m} p_i . Profit(s,l,k,p)_i$$

$$Where$$

$$Profit(s,l,k,p)_i = (1 - Tax\ Rate(s,l,k,p)_i)\ (Income(s,l,k,p)_i - Cost(s,l,k,p)_i)$$

$$Income(s,l,k,p)_i = Market\ Price(s,l,k,p)_i\ .\ \ Number\ of\ Sales(s,l,k,p)_i$$

$$Cost(s,l,k,p)_i = Initial\ Investment\ Seasonal\ Annuity(s,l,k,p)_i + Labor\ Cost(s,l,k,p)_i + Energy\ Cost(s,l,k,p)_i + Water\ Cost(s,l,k,p)_i + Transport\ Cost(s,l,k,p)_i + Maintenance\ Cost(s,l,k,p)_i + Material\ Cost(s,l,k,p)_i + Inssurance\ Cost(s,l,k,p)_i$$

Equation 8. Shows the expected profit for a single season (s+i)

Assuming that an investor would choose n seasons for the time of operations the expected profit for the entirety of n seasons is:

$$The\ expected\ Profit = \sum_{j=0}^{j=n} \sum_{i=0}^{i=m} p_{ij} . Profit(s,l,k,p)_{ij}\ .\ (\frac{P}{A}, MARR, j)$$

Equation 9. Illustrates the expected profit for the entirety of the project life (n)

It should also be mentioned that the proposed stochastic model for profit can be subject to change, if the empirical data illustrates a clear favorable stochastic process to be followed.

2.2.4 Risk Estimation

There are a variety of ways to approach risk management in the farming business. In this study, the risk factor is manifested in two forms. First, the insurance rate is taken into account in the Profit estimation segment. Second, as a measure of volatility, variance values of the Profit stochastic process are formulated. This risk indicator would be the sum of the different scenarios of profit in different seasons for the entirety of the investment period:

$$Risk = \sum_{j=0}^{j=n} S^2{}_j$$

$$Where:$$

$$S^2{}_j = \frac{\sum_{i=0}^{m} (Profit(s,l,k,p)_{ij} - The\ Expected\ Profit(s,l,k,p)\ _j)^2}{m-1}$$

Equation 10. The summation of the variance of the profit stochastic process in each season

2.2.5 Environmental Hazard

Equation 5 illustrates the parameters that influence the environmental hazards of a farming practice. In this study, as the goal is to formulate a big picture framework, it is assumed that decent estimations for the individual environmental parameters can be acquired for any season, location, scale, and product. In other words, it is assumed that values of *greenhouse gas emission, deforestation, waste,* and *irrigation* can be estimated for any (s, l, k, p) values. However, it should be noted that the mentioned four environmental hazards are measured in different units. Therefore, in order to formulate a singular linear model for total environmental hazards, the four parameters must be converted to same scale measurements. To that end, the standard scalar function is used here. Standard scalar is a popular standardization tool that is mostly used in machine learning data preprocessing, which rescales the data features so that they would have properties of a normal distribution with μ=0 and σ=1. Thus, *Standard scalar()* function is defined as follows:

$$Standardscalar(X_i) = \frac{X_i - \mu}{\sigma}$$

Equation 11. Standaridscalar

The next step would be to use the standard scalar function to provide an environmental hazard indicator by summing up different parameters. Subsequently this would mean a uniform distribution of importance among our environmental hazards parameters. Hence, the environmental hazard function for a particular season is defined as follows:

$$\begin{gathered} Environmental\ Hazard\ (s,l,k,p)_j = \\ Standardscalar\ (Green\ house\ emissions(s,l,k,p)_j) + \\ Standardscalar(\ deforestation(s,l,k,p)_j) + \\ Standardscalar(\ waste(s,l,k,p)_j)\ + \\ Standardscalar(\ irrigation(s,l,k,p)_j) \end{gathered}$$

Equation 12. A linear estimation of total environmental hazards by utilizing the standard scalar function

2.2.6 Objective Function

Using the functions defined in previous sections, here, a multi objective stochastic linear framework is defined in which the goal is to maximize the relative expected profit, minimize the relative expected risk and minimize the relative environmental hazards. To satisfy this model, one must find the values of s,l,k,p for a particular investor or decision maker that has a n season time frame in mind with a MARR minimum attractive rate of return.

$$\textit{Find s,l,k,p in condition that:}$$

$$Max\ Z = \ The\ Relative\ Profit =$$

$$Relative(\sum_{j=0}^{j=n}\sum_{i=0}^{i=m} p_{ij}.\,Profit(s,l,k,p)_{ij}\,.\,(\tfrac{P}{A},MARR,j))$$

$$Min\ Y = the\ relative\ Risk = Relative(\ Risk) = Relative\ (\sum_{j=0}^{j=n} S^2{}_j)$$

$$Min\ \ X = The\ relative\ Environmental\ Hazard =$$

$$Relative(\sum_{j=0}^{j=n} Environmental\ Hazard\ (s,l,k,p)_j)$$

$$s.t$$

$$n,m \in \mathbb{N}$$

$$n,m < \infty$$

$$MARR \in \mathbb{R}$$

$$0 < MARR < 1$$

Equation 13. A multi-objective model that can be used to evaluate vertical farming with respect to traditional agriculture

The three defined objectives are generally important to every investor or decision-maker. However, their relative importance can vary depending on the personal characteristics of a decision-maker. For instance, some investors might have a risk-taking personality and prioritize objective Z over objective Y. Another type of personal preference can be manifested in the way people feel about environmental hazards. Some people can be more environmentally conscious than others can. For example, a public agency doing macro-economic analysis might hold paramount objective X over objective Z, but that behavior can be very rare among private investors. Although Equation 13 provides the formulation of the three different goals, it is quite difficult to analyze each objective's relative importance in that formulation. Therefore, these three objectives will be converted into a single objective model formulation. Z, Y, and X have different types of values with different measurement units; hence, the standard scalar() function is utilized here to normalize all three values. Also, assume w1,w2,w3 that are relative importance indicators weights that a particular decision-maker assigns to objectives Z,Y, and X respectively where w1+w2+w3=1. Equation 14 provides the final linear objective function where w1,w2,w3 values are assigned by the decision-maker that utilizes the model based on personal preferences.

$$Max\ V = w1.Standardscalar\ (Z) - w2.Standardscalar\ (Y) - w3.Standardscalar\ (X)$$

Equation 14. The final linear objective function

2.3 Chapter summary and Conclusion

This chapter proposes a big picture framework that can be used as a first step towards assessing vertical farming systems from an economic standpoint. The proposed framework works to evaluate vertical farming as a business venture in comparison with traditional agriculture. Hence, three objectives are defined that should be met in order to find the optimized condition of implementing vertical farming systems. The objectives are maximizing the relative profit estimates, minimizing the relative risk and minimizing the relative environmental hazards. The framework takes five input values from any investor or decision maker in order to account for different character traits and personal preferences. n represents the amount of time that investor is looking to be involved in a vertical farming project and MARR represents their minimum attractive rate of return. Moreover, the model asks for three weight factor values (w) from the decision makers that would represent the relative importance of each individual objective from their perspective. Theoretically, an investor should solve the proposed stochastic model for *start season*, *location*, *scale*, and *product type* values that satisfy the objective function to find the optimum form of implementing vertical farming systems.

Although the provided model is quite comprehensive, it might prove too difficult to be utilized in experiments. We should bear in mind that vertical farming is a new industry where none of the operating businesses are publicly traded. Hence the publicly available data is minimal. Moreover, as previously mentioned, no prior scholarly research has attempted to estimate the influencing parameters discussed in this chapter. Hence, for this study's purpose, we must try to relax and simplify some aspects of the comprehensive model to generate practical results and test the model with real-world data.

3 THE REVISED MODEL

3.1 Redefining the Problem

In chapter 2, four state variables were defined that the model would eventually try to solve for, Start Season (s), Location (i), Scale (k), and Product Type (p). In an ideal scenario, we would be able to solve for the optimal values of all the mentioned state variables in a stochastic setting. However, there are only a few operating vertical farming ventures currently in the US, none of which are publicly traded. Thus, the available data is very limited. Frankly, to provide viable answers for each of the four state variables, one would either need a great number of publicly available data or a considerable amount of resources to acquire the said data. Otherwise, results generated based on the Chapter 2 model would be premature. There is no proper way to numerically formulate the stochastic probabilities of the Chapter 2 model without sufficient data, especially considering there have been no prior similar stochastic models in the literature. It is our hope that at some point in the future there will be enough data and resources available to practically implement the model proposed in Chapter 2. For this thesis, however, we need to redefine and simplify the model to generate viable and practical results. Hence, we will shift our focus to finding the optimum location for implementing vertical farming ventures in a competitive marketplace. This chapter works to revise the initial model to address the redefined and simplified problem definition. It should also be noted that due to intense complexity and lack of data, the environmental aspect of the Chapter 2 model will be relaxed altogether. In other words, this chapter seeks to propose a decision model that can be utilized for locating the best vertical farming location from a set of n alternatives by taking into account the cost/profit potential and risk.

3.2 Parameters and Relation

3.2.1 The Main States

In the previous chapter, four state variables were defined that the model would eventually try to solve for*, Start Season (s), Location (i), Scale (k), and Product Type (p)*. In this segment, we look to redesign the model to only solve for finding the optimum location for implementing vertical farming. To that end, we choose to keep the Location (i) state variable and relax the other three state variables.

Start season variable is relaxed by assuming that any established vertical farming would continue its work for a year in a single location. All of the parameters in questions from this point forward will be estimated assuming a full year of production for both the field grown and vertical farming operations.

Scale variable is relaxed by assuming a production capacity benchmark for both vertical and field grown farming. To provide a good representation of a practical vertical farming business practice, a review of the successfully operating vertical farming operations was carried out. Vertical farming practices are generally in the form of either container farms (Figure 6) or factory farms (Figure 5). Factory farms typically operate in a controlled warehouse environment and produce leafy greens/herbs. Container farming practices like Freight Farms (Freight Farms, 2020) on the other hand, typically have a different business model to begin with since their goal is to sell/rent a container equipped with vertical farming machinery rather than producing and selling crops themselves. Moreover, factory farms are generally more optimized and benefit from a much better cost efficiency due to their considerably larger scale. Thus, this study assumes that the stakeholder's goal is to sell crops rather than containers or machinery and a rational stakeholder that has access to sufficient funds would implement a factory farm over a container farm. Hence, vertical factory farms are the main subject assessment in this study. The most successful operating examples of factory farms in today’s market are Aerofarms (Aerofarms, 2020) and Technofarm (technofarm, 2020) operating in New Jersey, US and Japan, respectively. Using the limited data available on these two companies' operation details, we assume that the vertical farming venture discussed in this study has the scale to produce approximately 90,000 kg of lettuce per year.

Figure 5. Aerofarms (Aerofarms, 2020) vertical farming which is the most prominent factory farm using vertical farming

Figure 6. Evergreen lab's (Evergreen- Txstate, 2020) container vertical farming operation

Product variable is relaxed by assuming that the vertical farming venture in the discussion will only go to product Romaine lettuce. To provide a better perspective on the reasons behind this choice, one should consider the current technical feasibility and cost efficiency of farming different crops with vertical farming practice. Theoretically speaking, one can grow any type of product with vertical farming, ranging from leafy greens and vegetables to grains like wheat and rice. So, the better question to ask is whether it would be desirable to grow a certain product using vertical farming. There are a few important factors dictating the choices to grow a particular crop in vertical farming.

The most important influencing factor here is the required energy. Vertical farming trades off energy consumption to produce faster, with less risk, water, and better quality, in a smaller space. One important question one should ask about choosing products to grow with vertical farming is whether it would be worth spending that extra energy to gain better quality, higher production efficiency, etc. As of now, the answer to that question is "probably yes under some conditions" when asked about lettuce and leafy greens, but "no" when asked about other crops. There are a few reasons for that.

First, lettuce and leafy greens require a relatively small amount of energy (or sunlight) to grow. They also generally have a high "value to required space" ratio as well, which is due to their relatively low space requirement and high market value. In addition, if one looks at a produced leafy green, almost all portions of the produced crop are consumable, meaning the production value is a lot more efficient.

On the other hand, however, commodities like rice are the exact opposite. They require considerably more energy input to grow while taking up a lot of space to produce relatively small consumable portions. Hence, producing commodity crops with vertical farming without some serious innovations in the industry is not realistically feasible. As for vegetables like tomato or cucumber, etc. they fall somewhere in the middle of this tradeoff spectrum, not as bad as commodity products, and not as appealing as leafy greens. There has been limited production of vegetables like tomatoes recently, but the industry mainly chooses to produce leafy greens at this point. So, we assume that the vertical farming business venture examined in this study would only produce leafy greens. Also, due to the considerably larger market and the more common practice of producing lettuce among the vertical farming businesses compared to other herbs and leafy greens, the model would assume that the examined farming businesses will only produce romaine lettuce.

3.2.2 Unit Cost Per kg of Production

We should address that all of the variables from this point forward will be measured per kilogram unit in order to unify the measurement units of all the discussed parameters. This way, it will make it easier to carry out mathematical procedures on different factors.

3.2.3 Cost and Profit Margin Indicator

First, it should be noted that we chose to relax profit function illustrated in Equation 9 and convert it into a regional production cost indicator function. Very limited data on the sales information of vertical farming products was the main reason for this decision. For this study, we assume that all of the produced lettuce in our examined farms will be sold at their respective regional prices. We also assume the production costs per kg of production adjusted with regional market prices would provide a decent indicator representing a relative appeal of a certain market from a cost and profit margin potential perspective. So, let us define:

$$\text{Cost of production} = f(\text{ Labor Cost, Energy Cost, Rent Cost, Water Cost})$$
$$\text{Profit margin appeal of location } (i) = f(\text{ Cost of labor per kg}(i), \text{Cost of energy per kg}(i), \text{Cost of rent per kg}(i), \text{regional price per}(i)\text{ kg})$$

Equation 15. Cost of production relations

Since this study works to find the relative best location, the initial machinery investment would not influence the decision as it is more or less the same in any location in the study. Also, initial investments do not appear to be the main concern in this industry. Hence, we assume labor, energy, rent, and regional price provide an excellent indication of a certain location's cost appeal.

3.2.4 Risk

Vertical Farming could majorly contribute towards risk reduction as an alternative farming method. Also, we know that farming risk varies in different regions. In this segment, we assume that regional insurance rates and regional government subsidies are an accurate indicator of farming risk in a particular location. Insurance and subsidy rates themselves are affected by a variety of different influencing factors from the regional environmental conditions and the business performance to the public policy agenda. On a plus note, the US Department of Agriculture provides comprehensive insurance data on a county level with detailed rates, and we would be using that data in further model calculations.

It is a good assumption to believe that this insurance rate is a very decent estimation of the risks associated with business practice in a particular area considering that a number of expert economists using USDA's vast resources constantly update the rates based on historical production and regional weather patterns. It is fair to argue that the insurance rates provided by the US Department of Agriculture are probably the most accurate representation of farming risks in the US, which is also available numerically in large chunks of data. Let us define:

$$Regional\ Risk\ in\ Location(i) = f\,(\,Insurance\ rate\ (i),\ subsidy\ rate\ (i)\,)$$

Equation 16. Regional risk relations

3.3 Model Formulation

3.3.1 Regional Profit Margin Appeal Formulation

In this segment, we propose a regional cost appeal indicator model that would provide the relative economic appeal of a vertical farming business venture with respect to traditional agriculture in a particular marketplace. Table 1 illustrates the variables used in this indicator model, along with their descriptions and abbreviations.

Table 1. Provides descriptions for the parameters used to formulate the Regional Cost Appeal model

Name of the Variable	Unit	abbv	Description
Man Hour per kg	Man hour/kg	q1	the required hours of labor to produce a kg of romaine lettuce with a vertical farming practice
Energy Consumption Per kg	KwH/kg	q2	the required energy input to produce a kg of romaine lettuce with a vertical farming practice
Water Consumption Per kg	L/kg	q3	the required water input to produce a kg of romaine lettuce with a vertical farming practice
Land required per kg	M2/kg	q4	the land required to produce a kg of lettuce with a vertical farming practice. This parameter is scaled based on a yearly production of approximation 90,000 kg for each type of practice
Water price	USD/L	p1	Unit price of water in a region
Energy price	USD/KwH	p2	Unit price of energy in a particular region
Land rent price	USD/M2	p3	Unit price of rent in a particular region for particular practice form (vertical/field grown)
Labor price	USD/ManHour	p4	Unit price of labor in a particular region

Table 1. Continued

Lettuce Price	USD/kg	pr	Unit price of romaine lettuce in a particular region
Cost indicator function in location i	%	C	An indicator determining the economic appeal of implementing vertical farming in particular location
Man Hour per kg	Man hour/kg	Q1	the required hours of labor to produce a kg of romaine lettuce using traditional farming practices
Energy Consumption Per kg	KwH/kg	Q2	the required energy input to produce a kg of romaine lettuce using traditional farming practices
Water Consumption Per kg	L/kg	Q3	the required water input to produce a kg of romaine lettuce using traditional farming practices
Land required per kg	M^2/kg	Q4	the land required to produce a kg of lettuce using traditional farming practices. This parameter is scaled based on a yearly production of approximation 90,000 kg for each type of practice
Production Cost Per kg for vertical farming practice	USD/kg	CV	As defined in Equation 17
Production Cost Per kg for traditional farming (field grown) practice	USD/kg	CT	As defined in Equation 18
Profit margin of growing crops in location i with vertical farming practice	%	PV	As defined in Equation 19
Profit margin of growing crops in location i with traditional farming practice	%	PT	As defined in Equation 20
Relative profit margin appeal of growing crops in location i	%	PA	As defined in Equation 21

Now let us define the indicator model CV(i) which provides the production cost of a kg of crops in location i utilizing a vertical farming practice as follows:

$$CV(i) = (\sum_{j=0}^{j=4} p(i)_j . q_j)$$

Equation 17. The cost per kg of producing crops location i with vertical farming in location i

CT(i) is defined similarly to CV (i) only for a traditional farming (field grown) practice:

$$CT(i) = (\sum_{j=0}^{j=4} p(i)_j . Q_j)$$

Equation 18. The cost per kg of producing crops location i with traditional farming

Using the regional price (pr(i)) the profit margin for each type of practice based on production costs is defined as follows:

$$PV(i) = \frac{pr(i) - CV(i)}{pr(i)}$$

Equation 19. Profit margin for a vertical farming practice in location i

$$PT(i) = \frac{pr(i) - CT(i)}{pr(i)}$$

Equation 20 Profit margin for a traditional farming practice in location i

PV(i) and PT(i) provides us with marginal profit potentials of farming in a location with vertical and traditional practice, respectively. As defined in Equation 21, the relative profit margin potential for vertical farming is defined as PA(i) . This way, one can interpret the higher the PA(i) value in a location, the better is the potential of implementing vertical farming from a production cost and profit margin potential standpoint.

$$PA(i) = PV(i) - PT(i)$$

Equation 21. Relative profit margin appeal of implementing vertical farming in location i

Equation 21 provides an indicator function that can be utilized to estimate the relative appeal of a location for implementing a vertical farming operation with respect to traditional farming. It is important to understand the goal of this indicator is not to provide an exact estimation of the costs and profit margins associated with operating a farm in location a or b. Rather the PA(i) indicator's goal is to provide a viable indication on whether location a or b is the better choice to implement a vertical farming venture from an economic perspective. It should also be noted that this model relaxes several other costs factors. It is assumed that the machinery, tech, and maintenance costs are the same in every location, thus they would be irrelevant to the objective of the indicator. Also, as mentioned before this model only accounts for the costs directly associated with the production and it assumes that other factors like legal fees, marketing costs, transportation costs, number of sales, and tax will be similar in both vertical and traditional practices, thus their impact is negligible in the relative assessment.

3.3.2 Regional Risk Appeal Indicator

In this segment, a regional risk indicator is introduced to measure the risks associated with practicing traditional agriculture in a particular location. Table 2 describes the parameters used in this model.

Table 2. Parameter description, unit and abbreviation for variables used in the Risk Appeal indicator

Name of the Variable	**Unit**	**Abbv**	**Description**
Risk appeal indicator	USD/acre	RA	Description is given on Equation 22
Regional Insurance rate per acre	USD/acre	IR	Regional insurance rate per acre for producing a crop (lettuce in this case) with the common field grown traditional agriculture in a particular location
Regional Subsidy Rate	%	SR	Regional subsidy rate (provided by the federal government in the US) for producing a crop (lettuce in this case) with the common field grown traditional agriculture in a particular location

Let us define RA(i) as follows:

$$RA(i) = \left(1 - SR(i)\right).IR(i)$$

Equation 22. Risk appeal indicator for location i

RA(i) simply calculates the amount paid for traditional farming insurance in location i.

We should also address why we have not included any risk parameters relating to vertical farming in Equation 22. Like the previous indicator, we should first understand that the goal of this RA(i) is not to provide an accurate measurement of the risk probabilities and risk costs of either farming practice in a particular location. The risk appeal indicator's job is to find the comparatively more appealing location from a risk perspective. As for the vertical farming operating risk, it is commonly believed to have a very limited production risk. However, although vertical farming is considerably less risky than field grown operations, the argument for excluding vertical farming risk factors here is not the assumption that vertical farming risk is negligible. The argument here is that vertical farming operation risk is independent of its location as it is not reliant on the environment whatsoever, meaning a constant regardless of i. So, it can be excluded from the RA(i) which is a relative location based risk indicator since a constant value that would be the same in every location would not affect the comparative results of the risk appeal model or the possible decisions based on the relative appeal of a location.

To provide a better perspective, the higher RA(i) value for a location, the riskier it is to practice traditional agriculture and the more appealing it is to practice vertical farming from a risk aversion standpoint.

3.3.3 The Decision Model

Two location appeal indicators were proposed in Equation 21 and Equation 22 which assess the suitability of implementing a vertical farming venture in any location based on the profit margin and risk aversion potential, respectively. In this segment, we seek to propose a decision model based on the two indicators. First, we should acknowledge that the values provided by PA(i) and RA(i) are different in nature and scale. So, in order to merge the two indicators into a decision model it is needed to scale the values to a singular scale. To that end, a normalization tool commonly known as minmax scalar is utilized here to normalize all the values into a 0 to 1 range. Let us define minmaxscalar() (statisticshowto, 2015) for a data set as:

$$minmaxscalar\ (X(i)) = \frac{X(i) - X_{min}}{X_{max} - X_{min}}$$

Equation 23. minmax scalar function

Equation 23 normalizes the values of a data set between 0 and 1 based on the minimum and maximum values of the said set. In chapter 2, we had initially proposed using standard scalar (Equation 11) which would carry out a similar function by rescaling a set on a normal distribution. However, considering that we seek to examine 7 locations in this study, our standardization set is relatively small, hence, minmax scalar is a more suitable tool in this case.

Using the minmax scaling tool let us define Profit Decision Indicator (PDI) and Risk Decision Indication (RDI) as follows:

$$PDI(i) = minmaxscalar(PA(i))$$

Equation 24. Decision indicator based on regional costs

$$RDI(i) = minmaxscalar(RA(i))$$

Equation 25. Decision indicator based on regional risk

We know the higher the value of RDI(i) and PDI(i) the more appealing a location is for implementing a vertical farming operation. However, the relative importance of profit margin and risk differs from one decision maker to another. For instance, a risk averse investor who is not comfortable with high risks associated with traditional farming would put more emphasis on a high value of RDI(i) compared to PDI(i). Of course, a risk taker on the other end of the spectrum might do the exact opposite. Hence, stakeholders' preferences must be taken into account to design a decision model. To that end, let us define w1 and w2 that would represent that relative importance of PDI(i) and RDI(i) respectively, where:

$$w1 + w2 = 1$$

Equation 26. w1 and w2 representing the relative importance of cost and risk in a decision

Now let us define the final Location Appeal (LA(i)) function based on the previous indicators:

$$LA(i) = (w1.PDI(i)) + (w2.RDI(i))$$

Equation 27. The final location appeal indicator

The LA(i) function would provide a score ranging between 0 and 1 that would indicate the relative appeal of a location for implementing vertical farming based on the relative economics, regional risks and investor's preferences. The higher the value of LA(i), the more appealing location i is for pursuing a vertical farming business venture and vice versa.

The following decision model can be utilized if one were looking to find the best location for implementing a vertical farming business based on the proposed indicators from a set of n locations.

Find the optimum i in a condition that:

$$MAX\ Z = LA(i)$$

Where:

$$i = \{location1, location\ 2, \dots location\ n\}$$

Equation 28. The decision model for locating the best vertical farming location

4 A DECISION SUPPORT SYSTEM

4.1 General System Description

In this chapter, the models and indicators presented in Chapter 3 are utilized to design and implement a model-based Decision Support System (DSS) (Keen, 1980). This system could help investors or other stakeholders choose the most suitable locations for implementing vertical farming from a range of alternatives. The DSS can also help any stakeholder gain more insights about each of the location alternatives. Figure 7 illustrates the interactions of the system with the outside world.

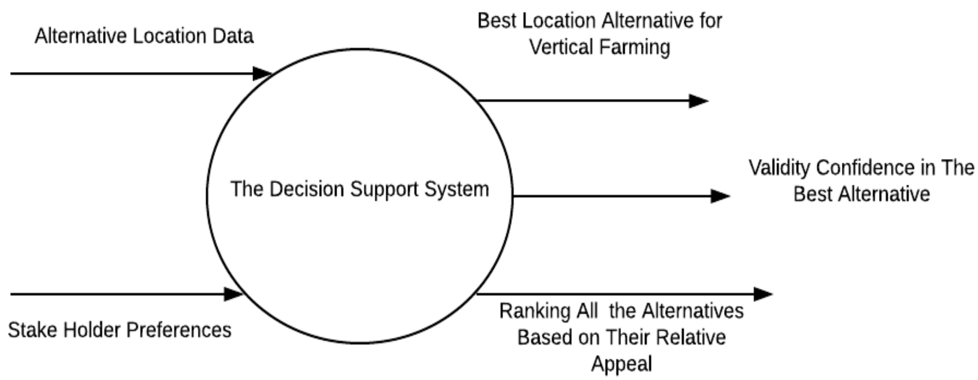

Figure 7. System general inputs and outputs

4.2 The Goal of the System

It is important to review the system objectives before designing any systems. The proposed DSS is designed to help an investor or a stakeholder choose between several locations that are being considered for implementing a vertical farming business. To that end, the system would acquire an alternative list from a user and examine the relative appeal of those alternatives based on the local algorithms and datastores embedded within the system. Moreover, the system would validate the examination with sensitivity analysis and generate the results along with their confidence level to help the user make the best decision.

4.3 Datastores

The proposed system has six data stores which are discussed here:

4.3.1 Traditional Farming Practice Data

This datastore holds related values to the practice of traditional farming regardless of location. These values include Land Requirement per kg, Water Consumption per kg, Energy Required Per kg, and Man Hour per kg. Figure 8 illustrates the Traditional Farming Practice datastore.

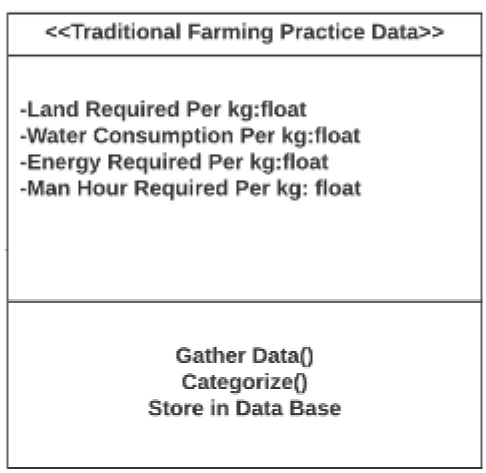

Figure 8. Traditional farming practice data

This information is acquired by reviewing the existing literature and practicing businesses (urbanagnews, 2020) (Barbosa, 2015), (Galinato, 2013), (Toyoki Kozai, 2016), (Djevic, 2009), (allardo M, 1996), (Hussain, 2009). The information acquired from these sources is processed and checked for validity. Fortunately, most of the reviewed sources were very similar in their estimations. After removing questionable sources and adjusting for parameters such as scale, products, currencies, etc., a series of average benchmark values relating to "Traditional Farming Practice Data" is generated, as seen in Table 3. It is very important to address that the system would account for any possible errors in the estimated benchmark values by conducting sensitivity analysis.

Table 3. Benchmark values for practicing tradition agriculture

Parameter	**Traditional Agriculture (filed grown)**
Production per year benchmark (kg)	907184.7
Labor per kg (manH/kg)	0.014
Energy consumption per Kg (KWH/kg)	0.575
Water consumption per kg (L/ Kg)	250
Yield (Kg/M^2/Year)	4
Land ratio for 1 kg production in a year(M^2/kg)	0.25

4.3.2 Vertical Farming Practice Data

This datastore holds related values to the practice of vertical farming regardless of the location. These values include Land Requirement per kg, Water Consumption per kg, Energy Required Per kg, and Man Hour per kg. Figure 9 illustrates the Vertical Farming Practice datastore.

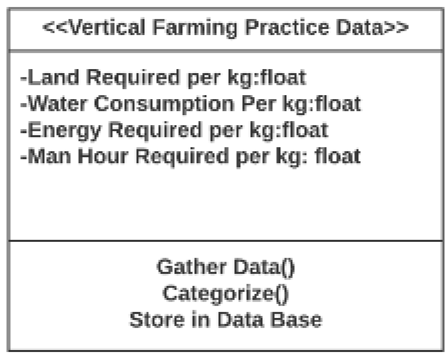

Figure 9. Vertical farming practice datastore

This information is acquired by reviewing the limited literature available along with the existing vertical farming businesses that successfully operate in today's economy (Toyoki Kozai, 2016) (Helmer, 2019) (IGrow, 2015), (Technofarm innovation, 2020), (urbanagnews, 2020), (Tasgal, 2019), (cambridgehok, 2020), (SPREAD, 2020), (Barbosa, 2015). The information acquired from these sources is processed and checked for validity. Fortunately, most of the reviewed sources were very similar in their estimations. After removing questionable sources and adjusting for parameters such as scale, products, currencies, etc., a series of average benchmark values relating to "Vertical Farming Practice Data" are generated, as shown in Table 4. Due to the tedious nature of this processing, only the final benchmark is provided here.

Table 4. Estimated benchmark values for a vertical farming practice

Parameter	**Vertical Farming**
Production per year benchmark	907184.74
Labor per kg (manH/kg)	0.066666667
Energy consumption Per Kg (KwH/kg)	5.75
Water consumption per kg (L/ Kg)	20
Yield (Kg/M^2/Year)	150.2334586
Land ratio for 1 kg production in a year (M^2/Year)	0.006656307

4.3.3 Risk Data

This store would hold the necessary data to calculate the risk appeal related function, including RA() and RDI() for every location. The required information to form this datastore is accessible through publicly available insurance data published by the US Department of Agriculture (USDA- NASS, 2020). Figure 10 illustrates the risk data series held by the system.

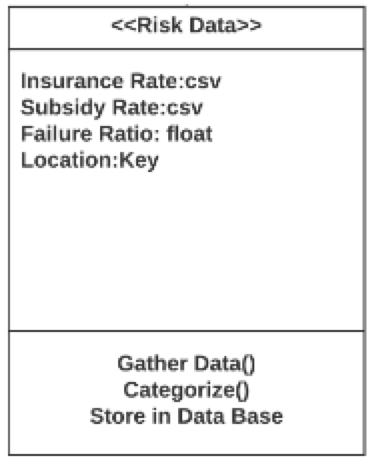

Figure 10. Risk datastore

The code used to process and extracted the needed information from a USDA dataset is copied in Appendix A of this document (Code 3. Acquiring risk and insurance data part 1, Code 2. insurance data)

4.3.4 Models

A series of models, indicators, and functions that were defined in chapter 3 are stored in this data class to be utilized in examining the suitability of different alternatives. Models datastore is defined as illustrated in Figure 11.

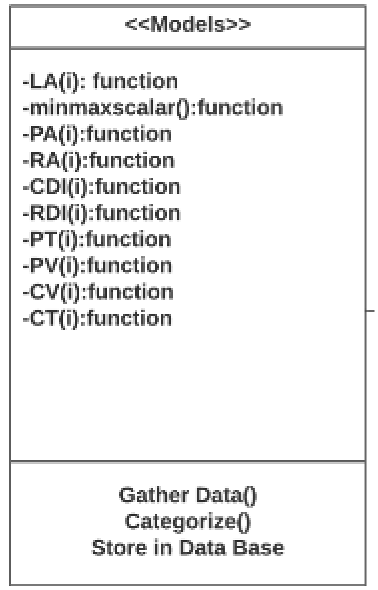

Figure 11. Models datastore

4.3.5 Alternative Location Data

This datastore plays a major role in providing the necessary information to the system for analyzing the location aspect of the evaluations. This data is usually provided by the user and read from the risk datastore. Alternative Location datastore is defined as illustrated in Figure 12.

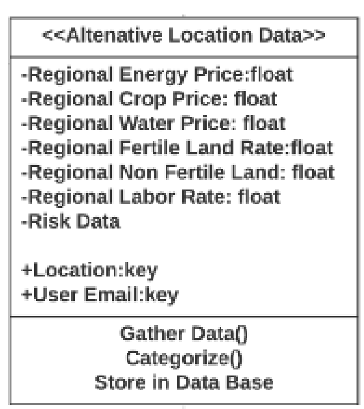

Figure 12. Alternative location datastore

4.3.6 User Data

This information, which includes the Alternative Location Data, stakeholder preferences, and user identifiers, is collected from the user and stored in the user data store, which is designed as shown in Figure 13.

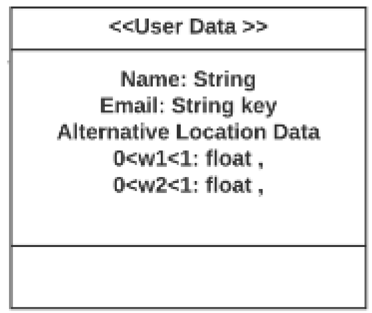

Figure 13.User datastore

4.4 User

The proposed system has only one type of user-defined as a “stakeholder”. The stakeholder user can be anyone who has an interest in assessing the economic and/or risk appeal of vertical farming among different location alternatives. This could be to help with a decision regarding private investments, public policy, research, etc. The user provides a series of information to the system, including personal preferences and alternative locations, and the system will provide the user with a suggested decision along with the subsequent analysis report. The user class of the system is defined as follows:

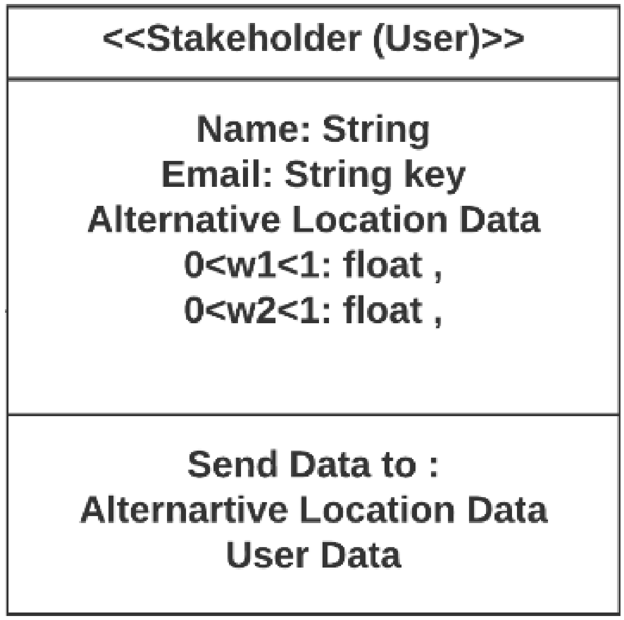

Figure 14. Stakeholder user class

4.5 System Processes

The proposed system has one main function, and that is to reliably quantify the relative appeal of the alternatives provided by the user and generate a decision suggestion. We will define this major process as the “Evaluation Process,” which will receive data from built-in data stores in the system, conduct a valid evaluation of the alternatives, and generate a report of the evaluation along with the suggested decision. The surface-level evaluation process is illustrated in Figure 15. The evaluation process has three important sub-processes that will be discussed to improve the system's understanding.

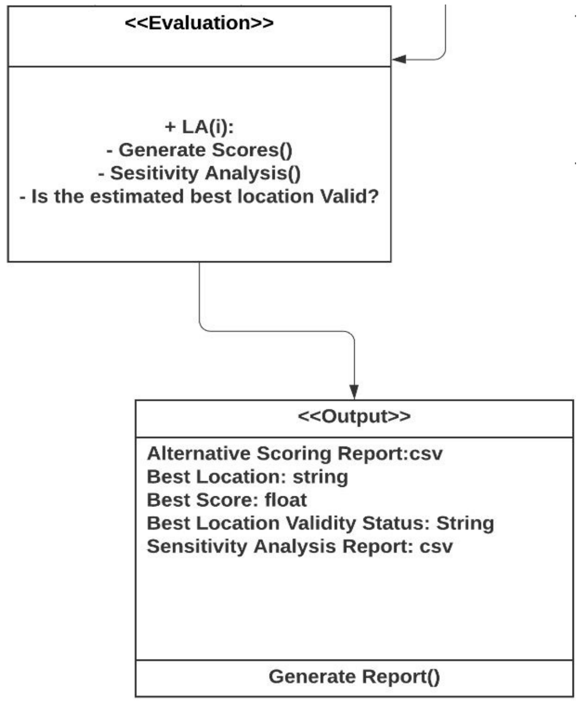

Figure 15. Evaluation and output class

4.5.1 Generating Scores

The first step in the evaluation process is to calculate the PA(i) and RA(i) for each location alternative, respectively. Then the LA(i) function and the w1,w2 preferences will be used to generate an appeal score for each alternative ranging from 0 to 1 where 1 is the most appealing and 0 is the least appealing location.

4.5.2 Sensitivity Analysis

We should bear in mind that benchmark values assumed for vertical and traditional farming practice (energy consumption per kg, etc.) although derived from a sufficient number of credible sources, can still vary from business to business depending on the technology of operations and farming efficiency. Even though these are technically independent of farming locations, a series of sensitivity analyses would greatly increase the confidence level in the decision suggested by the system. Hence, two extreme sensitivity analysis scenarios are proposed here to take into account the possible extreme advances and declines in the form that a vertical farming business operates, respectively.

Scenario 1: In this scenario, we assume that vertical farming practice would advance, and the operations would uniformly consume 25% less energy, 25% less labor, 25% less water, 25% less space required (Table 5)

Scenario 2: In this scenario, we assume that vertical farming practice would decline, and the operations would uniformly consume 25% more energy, 25% more labor, 25% more water, 25% more space required (Table 5).

The system would generate new scores based on these two extreme scenarios. We should also note why the scenarios have only been designed for the vertical farming practice form. The system generates relative scores, so a more efficient vertical scenario would be very similar to a less efficient traditional farming scenario. Moreover, traditional farming's related parameters are generally more established due to their long history and available resources.

The scores generated for each of the extreme scenarios would be provided to the user in a report and would help the system to assess the confidence level in the best location alternative.

Table 5. Scenario 1 and Scenario 2 for vertical farming

Parameter	**Scenario 1 for Vertical Farming Values**	**Scenario 2 for Vertical Farming Values**
Production per year benchmark (kg)	907184.74	907184.74
Labor per kg (man hour/kg)	0.05	0.083
Energy consumption per Kg (kwh/kg)	4.31	7.18
Water consumption per kg (L/ Kg)	15	25
Yield (kg/ m^2/Year)	187.79	112.67
Land ratio for 1 kg production in a year(m^2/kg)	0.0053	0.0088

4.5.3 Decision Confidence Level

Based on the sensitivity analysis done in the previous segment, the system would seek to examine the confidence level of the best location alternative. So, let us define the Confidence() function for the system, as illustrated in Code 1 using python. The higher the confidence () value, the higher the system's confidence in the best location chosen. If the best location chosen by the system is the same for all scenarios, that alternative is shown to be the best choice even after accounting possible benchmark errors and possible advancements and declines in the practice. This confidence level (0,0.5,1) value will be reported to the user along with the scores generated for both sensitivity analysis scenarios.

```
import numpy as np



def Confidence ( Best_ScoreLocation_general, BestScoreLocation_Scenario1,
BestScoreLocation_Scenario2):

if BestScoreLocation_General == BestScoreLocation_Scenario1 and
BestScoreLocation_General == BestScoreLocation_Scenario2: Confidence = 1

else:

    if BestScoreLocation_General == BestScoreLocation_Scenario1 or
BestScoreLocation_General == BestScoreLocation_Scenario2: Confidence =
0.5

    else:
```

Code 1. Defining confidence level function

4.6 Data Flow Diagram

Data Flow Diagrams (DFD) are a very common tool in clearly illustrating the flow of data within a system (Gane & Sarson, 1977). The DFD for the proposed Decision Support System is illustrated in Figure 16.

One can see that the system operator would first plug in the required data as described in the datastore segment into its respective data stores. Moreover, the stakeholder (user) would provide the necessary data to the system (please see Figure 14 for the exact data entered by the user). Then, the evaluation process (please see "Figure 15 System Processes " for specifics) would use the data entered by the user and called from the datastores to evaluated the alternatives and generate a report to the user.

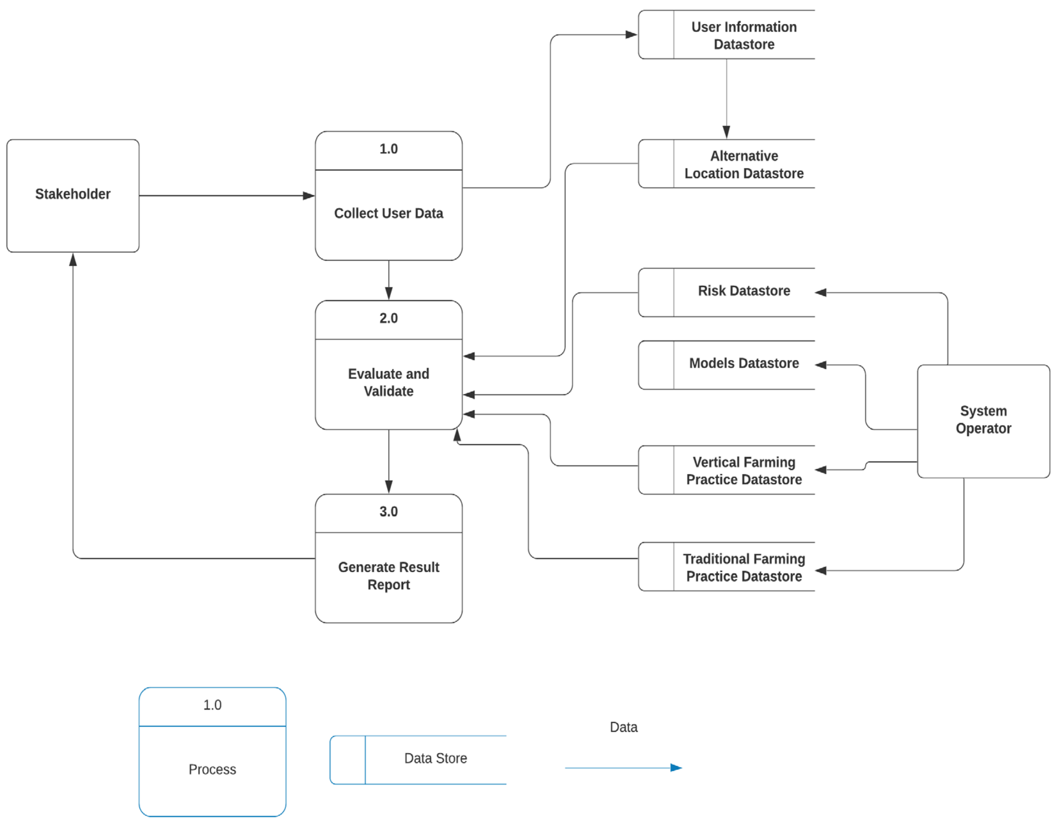

Figure 16. System DFD

4.7 Class Diagram

Class Diagrams are a very useful and common form to describe the structure of a system by illustrating systems classes, operations, and relationships among its objects (Sparks, 2011). The class diagram for the proposed Decision Support System is presented in Figure 17.

The class diagram basically shows all objects of the proposed systems and their relationship with one another. In our system's case, these objects include the six datastores, the Stakeholder user and the evaluation process.

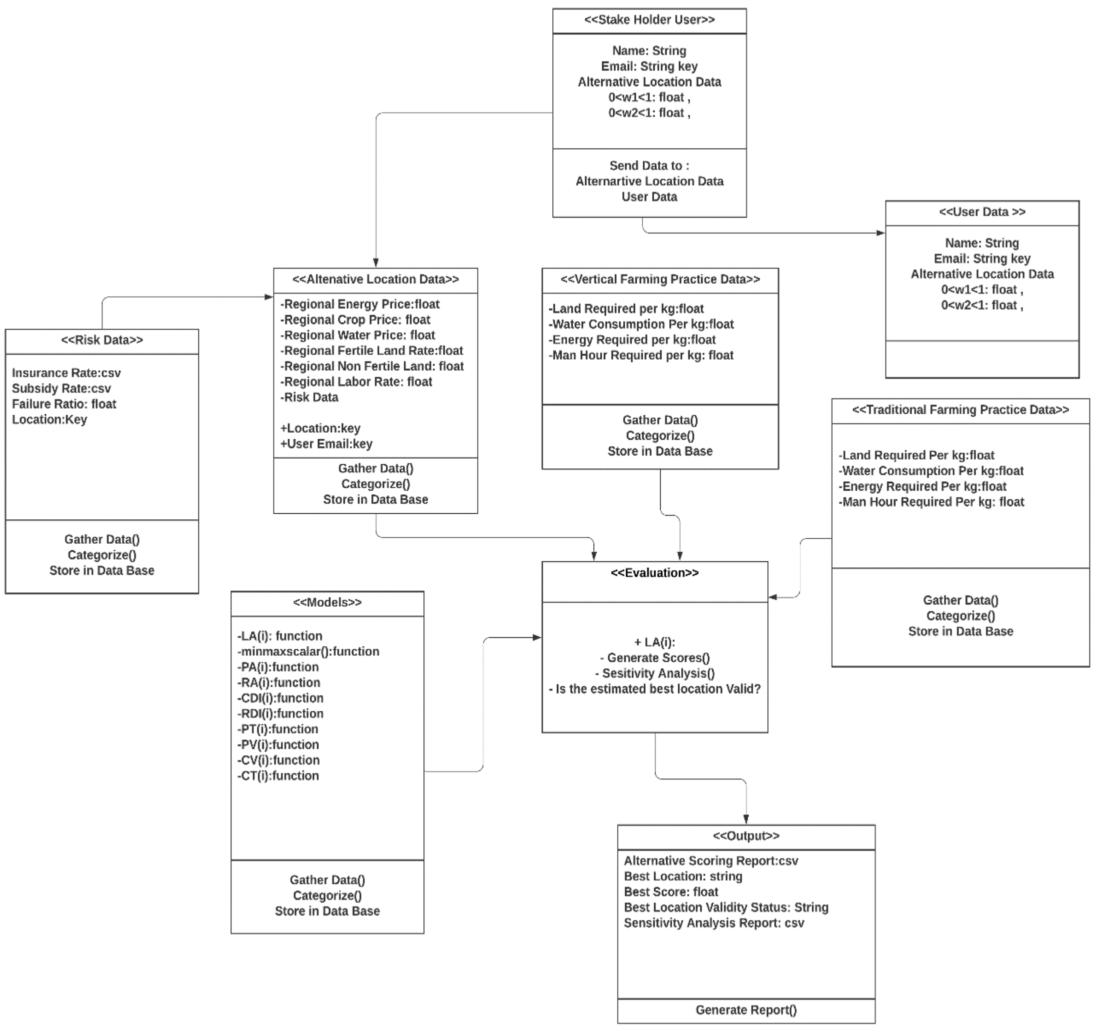

Figure 17.Class Diagram of the proposed Decision Support System

4.8 The Comprehensive Flow Chart

In this segment a comprehensive flowchart is provided to better illustrate the operations of the system along with its interactions with the user that were discussed in the previous segments.

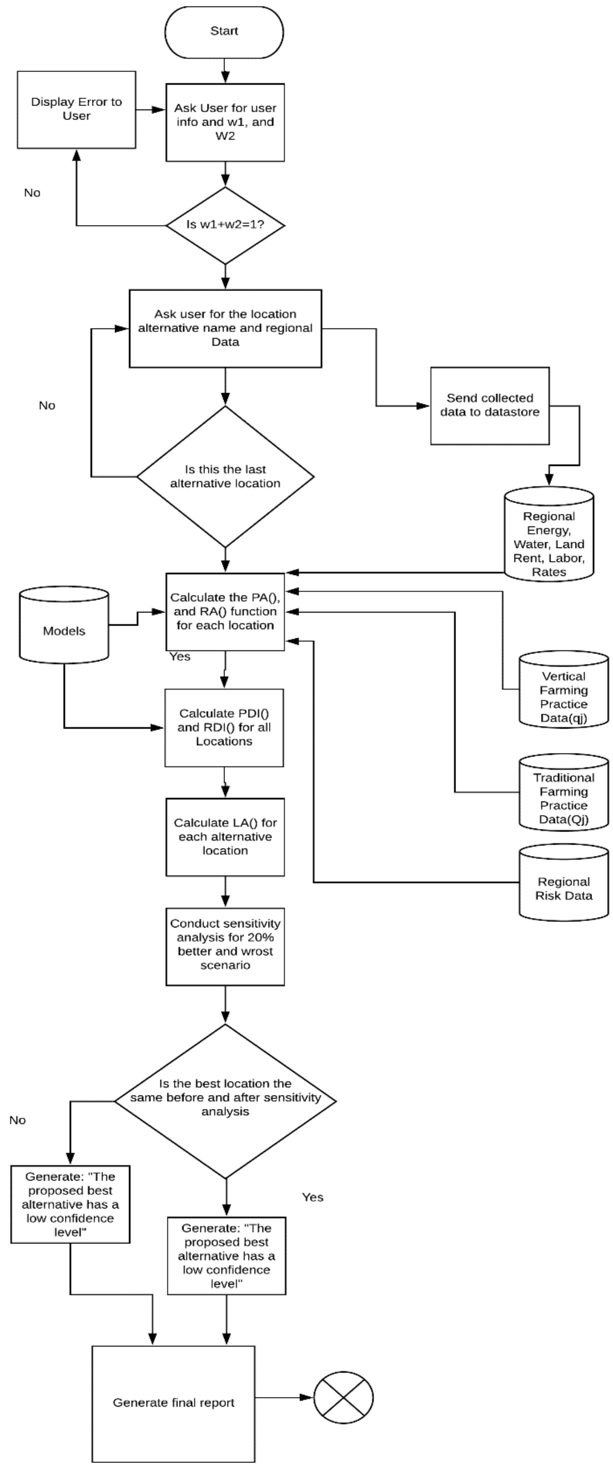

Figure 18. System comprehensive flowchart

4.9 System Implementation

As of this moment, a primary version of the system has been developed by utilizing python and excel. This primary system will be used in the next chapter to conduct a limited case study. It should be noted that the current developed system is not fully automated and is not suitable for consumer use. That said, developing a fully automated system based on the proposed design is an appealing task. Django (Django, 2020) framework is an attractive tool that can be considered for implementing the proposed system on a web environment.

4.10 Verification

To verify that the model is running without error, the following were checked:

- All processes are labeled correctly
- All connection points are linked
- All processes have resources
- All functions and equations calculate the same values inside and outside the system
- All decision points are connected to the specific processes
- All resources are unique
- All units are correct for each operation
- Replicant alternatives provide the same results by the system
- The system runs error-free
- The system behaves as expected for the extreme cases

4.11 Conclusion

This chapter proposes a Decision Support System that can be utilized to qualitatively assess the economic appeal of implementing a vertical farming business among a set of alternative locations in a competitive marketplace. To the best of our knowledge, there has never been a prior system in the literature or the private sector with similar functionality. The system considers the users' personal preference regarding risk and profit margin to be able to provide services to long-range stakeholders and adjust the relative appeal of different alternatives, respectively. The proposed system has the potential to attract a variety of different users. Private or corporate investors looking to invest in farming can use the system to support their decision making. Public policy stakeholders could use the system to understand the landscape of this novel and sustainable technology for future policies, as well as examining the impact of new and existing policies. For instance, policymakers could use the system to assess the impact of traditional farming subsidy rates on the landscape of the vertical farming industry. The proposed system can also be used by scholars to conduct more research on the economic aspect of vertical farming, which is deeply needed by the industry.

One of the features of the proposed system is that the more data it acquires, the more accurate its analysis and estimations. In other words, imagine that the system has processed more than 10,000 alternatives from different users at some point in time; not only would this mean that the systems scoring and scaling algorithm would be considerably more accurate, but also it would turn the system into a very valuable data source on vertical farming, a source lacking at this time. If enough data is acquired by the system, new evaluation methods such as statistical analysis or machine learning can be introduced to the system to solidify its performance.

For future work on the proposed Decision Support System, the first step should be to develop a fully automated, interactive web-based interface for users. Introducing more evaluation and validation algorithms as the system acquires more data can be another task for the future of this system. In addition, introducing a decision factor under the title “environmental hazards” as introduced in chapter 2 can be quite appealing as well. Finally, if enough data is gathered, one can look to introduce elements of probability into the system and convert the deterministic decision-making system into a stochastic one.

5 CASE STUDY

In this chapter, the system proposed in chapter 4 is utilized to conduct a series of experiments that examine the appeal of implementing vertical farming in different locations under different scenarios. Results generated based on these experiments could identify the most suitable locations for vertical farming and help provide a more in-depth understanding of pursuing vertical farming as a business practice. A series of sensitivity analysis procedures are conducted to examine the validity of the generated results. Finally, a subsection is dedicated to discussing the future of the vertical farming industry based on the case study results.

5.1 Locations

Let us first clarify the borders of the analysis in this segment by selecting seven metropolitan areas located in the US as the subject of this study. A list of the locations examined in this study is provided in Table 6. The locations are selected in a manner to provide a comprehensive perspective into the application of vertical farming in different areas of the US. Each selected location has certain characteristics that make it interesting to investigate. For instance, Austin has relatively cheap energy prices, Des Moines is located around conventional farming hubs, and New York and Boston are highly populated areas that currently house the pioneers of vertical farming industry. Moreover, the selected locations are scattered across the US and cover a broad range of environmental conditions (Figure 19).

Table 6. Location list

City Name	State Initial
Austin	TX
Boston	MA
Chicago	IL
Des Moines	IA
Los Angeles	CA
Miami	FL
New York	NY

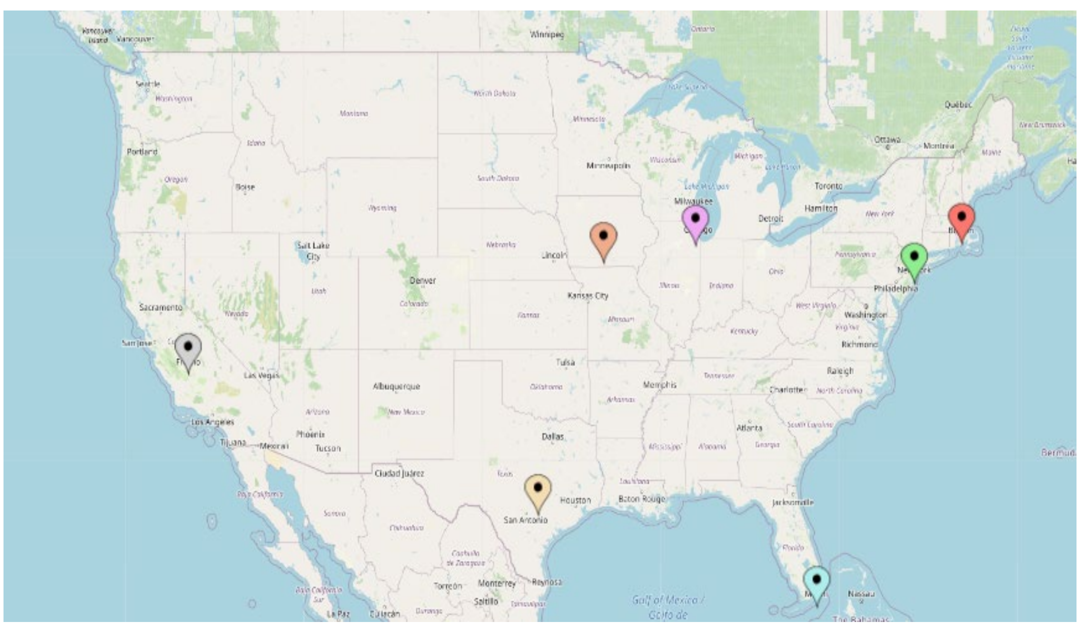

Figure 19. Seven locations selected for the case study

5.2 Alternative Location Data

We had previously discussed that the "stakeholder" would provide the system with required alternative location data which includes the material stated in Figure 12. In this segment, we gather the alternative location data along with credible sources for all the seven locations. It is important to note two important assumptions during this data collection. First, we assume that both vertical and traditional farming practices operate under industrial energy rates. Second, we assume that traditional farming practice needs fertile land to grow while vertical farming can operate on non-fertile land as it does not require any soil.

5.2.1 Regional Labor Rates

The median labor rate for each alternative location collected through federal and state labor and statistics departments is shown in Table 7.

Table 7. Regional farming labor rates

City Name	State Initial	Median Farm Labor Cost (USD/Hour)	Source
Austin	TX	11.61	(US Department of Labor and Statistics, 2020)
Boston	MA	17.36	(US Department of Labor and Statistics, 2020)
Chicago	IL	16.60	(US Department of Labor and Statistics, 2020)
Des Moines	IO	14.60	(US Department of Labor and Statistics, 2020)
Los Angeles	CA	16.00	(US Department of Labor and Statistics, 2020)
Miami	FL	12.67	(US Department of Labor and Statistics, 2020)
New York	NY	15.60	(NY Department of Labor and Statistics, 2020)

5.2.2 Regional Energy Rates

The regional industrial energy rate for each alternative location collected through the US Energy Information Administration is illustrated in Table 8.

Table 8. Regional energy rates. Source

City Name	State Initial	Industrial Energy Rate (USD/KWH)	Source
Austin	TX	0.054	(US Energy Information Administration , 2020)
Boston	MA	0.139	(US Energy Information Administration , 2020)
Chicago	IL	0.066	(US Energy Information Administration , 2020)
Des Moines	IO	0.062	(US Energy Information Administration , 2020)
Los Angeles	CA	0.12	(US Energy Information Administration , 2020)
Miami	FL	0.072	(US Energy Information Administration , 2020)
New York	NY	0.052	(US Energy Information Administration , 2020)

5.2.3 Regional Land Rental Rates

Regional fertile and non-fertile land rates were acquired through sources published by the US Department of Agriculture. It is assumed that traditional farming would need fertile land for the practice, while vertical farming would rationally choose the cheaper non-fertile land option for the practice. Table 9 illustrates the regional rates for renting land. It should also be addressed that these rates are not assigned to the borders of a city, which would obviously be a lot more expensive. Rather these rates represent locations that are in close proximity to the target market.

Table 9. Regional land rental rates

City Name	State Initial	Fertile Land Monthly Rent (USD/Acre)	Non- Fertile land rent (USD/Acre)	Source
Austin	TX	42.5	6	(USDA, 2020)
Boston	MA	88.5	35	(USDA, 2020)
Chicago	IL	224	41	(USDA, 2020)
Des Moines	IO	230	59	(USDA, 2020)
Los Angeles	CA	423	13	(USDA, 2020)
Miami	FL	110	15.5	(USDA, 2020)
New York	NY	66	26	(USDA, 2020)

5.2.4 Regional Insurance and Subsidy Rates

The regional insurance and subsidy rates for the entire US were acquired and entered into the system, as discussed in section 4.3.3. Table 10 provides the average regional and subsidy rates for the year 2018. It is assumed that risk factors from the previous years are realized in insurance calculations of the year 2018. Also, the year 2018 is chosen since some of the farming failures for 2019 and 2020 were not realize at the time of acquiring this data. Also, we should bear in mind that these numbers are in no way representing the exact insurance and subsidy rates for a particular lettuce farming practice. The provided values are only general indicators for having to provide a better understanding of the regional farming risks in each alternative location.

Table 10. Regional insurance and subsidy rates

City Name	State Initials	Subsidy%	Premium per Acre (USD/Acre)	Source
Austin	TX	0.7	74	(USDA-NASS, 2020)
Boston	MA	0.63	160	(USDA-NASS, 2020)
Chicago	IL	0.57	43	(USDA-NASS, 2020)
Des Moines	IA	0.54	32	(USDA-NASS, 2020)
Los Angeles	CA	0.59	31	(USDA-NASS, 2020)
Miami	FL	0.63	53	(USDA-NASS, 2020)
New York	NY	0.7	26	(USDA-NASS, 2020)

5.2.5 Regional Water Rates

Regional water rates acquired from a report published by the US Department of Energy are listed in Table 11.

Table 11. Regional water rates

City Name	State Initial	Water Price (USD/L)	Source
Austin	TX	0.0012	(US Department of Energy, 2017)
Boston	MA	0.0014	(US Department of Energy, 2017)
Chicago	IL	0.0012	(US Department of Energy, 2017)
Des Moines	IO	0.001	(US Department of Energy, 2017)
Los Angeles	CA	0.0016	(US Department of Energy, 2017)
Miami	FL	0.0012	(US Department of Energy, 2017)
New York	NY	0.0014	(US Department of Energy, 2017)

5.2.6 Regional Price of Lettuce

The retail price of Romaine lettuce for each alternative location is gathered from a local wholefoods store on June 2020 and illustrated in Table 12.

Table 12. Regional lettuce prices

Location	State	Price (USD/Head)	Source
Austin	TX	1.99	(Wholefoods Market, 2020)
Boston	MA	1.79	(Wholefoods Market, 2020)
Chicago	IL	1.99	(Wholefoods Market, 2020)
Des Moines	IO	1.99	(Wholefoods Market, 2020)
LA	CA	1.79	(Wholefoods Market, 2020)
Miami	FL	1.99	(Wholefoods Market, 2020)
New York	NY	1.49	(Wholefoods Market, 2020)

5.3 Experiment: Analyzing the Location Alternatives

5.3.1 The Alternative Appeal: The Risk Taker Stakeholder

In this segment, we seek to analyze the appeal of the alternative locations from the perspective of a relatively risk-taking stakeholder. This particular stakeholder has more emphasis on the relative profit margin potential of vertical farming than the risk aversion potential. Therefore, w1 and w2 values are set at 80% and 20%, respectively. The alternative location data gathered into section 5.2 are first converted to unit values compatible with the system and entered to the system.

Figure 20 illustrates the relative economic appeal of each location alternative. Table *13* provides a detailed report of the indicator functions for the evaluated alternative locations. A detailed copy of the system worksheet is also provided in the attached Appendix B.

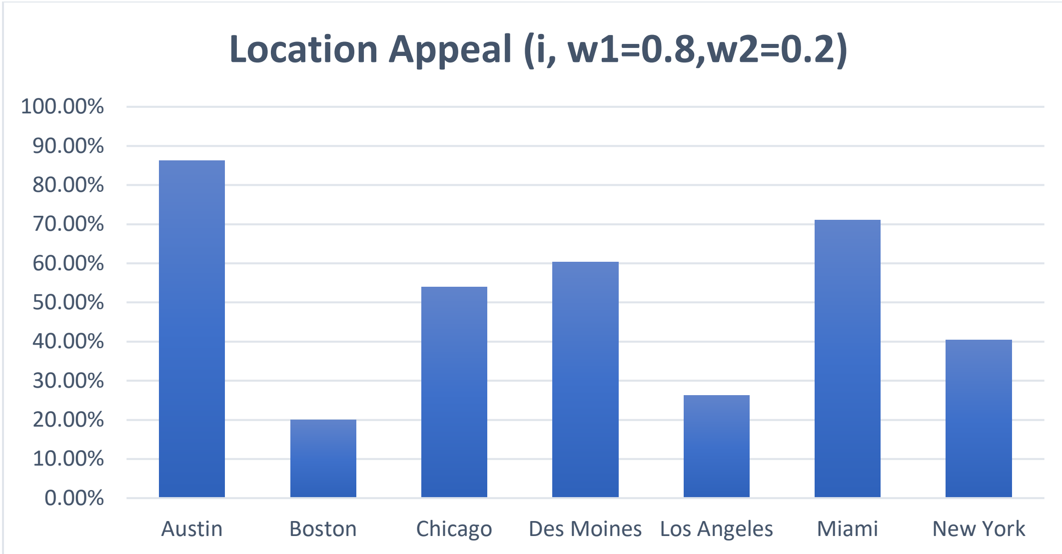

Figure 20. LA(i) with w1=0.8, w2=0.2

Table 13. System report for alternative evaluation. Please find abbreviation definitions in Table 1 and Table 2

City Name	PA	PDI	RA	RDI	LA(i, w1=0.8,w2=0.2)
Austin	-13%	100.00%	22.20	31.16%	86.23%
Boston	-32%	0.00%	54.02	100.00%	20.00%
Chicago	-21%	62%	18.49	23.13%	54%
Des Moines	-19%	72%	14.72	14.97%	60.3%
Los Angeles	-26%	30%	12.71	10.62%	26.27%
Miami	-17%	82%	19.61	25.55%	71.06%
New York	-23%	51%	7.80	0.00%	40.43%

It can be seen that the system assigns the highest location appeal score to the city of Austin, TX. We can also see that Miami and Des Moines are also shown to be somewhat appealing locations for implementing vertical farming, relatively speaking. High land prices in Iowa and Miami's low energy rates could be the reasons for this result. Austin also seems to have the highest PDI score, along with the second-highest RDI values. This, among other factors, can be because Austin has relatively cheaper energy and labor rates while having a relatively high market value of lettuce. We should also note that insurance rates around Austin are not low either, which contributes to the system choosing Austin as its favorite location. We should also have in mind that while Austin is the most economically appealing alternative to implement vertical farming, traditional farming still has a considerable cost efficiency advantage over any form of vertical farming as it can be seen in the PA() column of Table 13.

5.3.2 Sensitivity Analysis

Here, a series of sensitivity analyses are conducted based on the scenarios discussed in section 5.3.2 . This sensitivity analysis helps validate the generated results and checks the robustness of the system decision.

5.3.2.1 Scenario 1

In this scenario, we assume that vertical farming operations have become 25% more efficient, which could be due to the plausible growth of technology in the future or simply implementing a superior technology when compared to the benchmark estimates of the system (Table 5, Table 4, Table 3). The results for scenario 1 sensitivity analysis are presented in Figure 21.

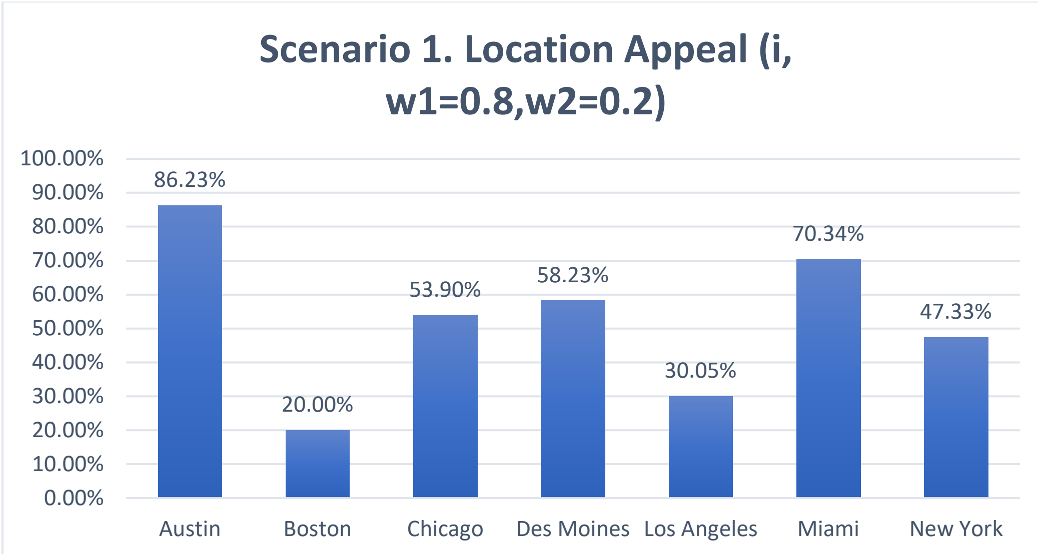

Figure 21. Scenario 1 scores

It can be seen from the results (Figure 21) that in the event of implementing a superior vertical farming technology relative to the current benchmark of the industry, Austin would still be the best location alternative. Moreover, Miami and Des Moines are still the second and third best choice, respectively.

5.3.2.2 Scenario 2

In this scenario, we assume that vertical farming operations have become 25% less efficient, which could be due to possible errors in benchmark estimations or simply implementing an inferior technology compared to the benchmark estimates of the system (Table 5, Table 4, Table 3). The results for scenario 2 sensitivity analysis are presented in Figure 22.

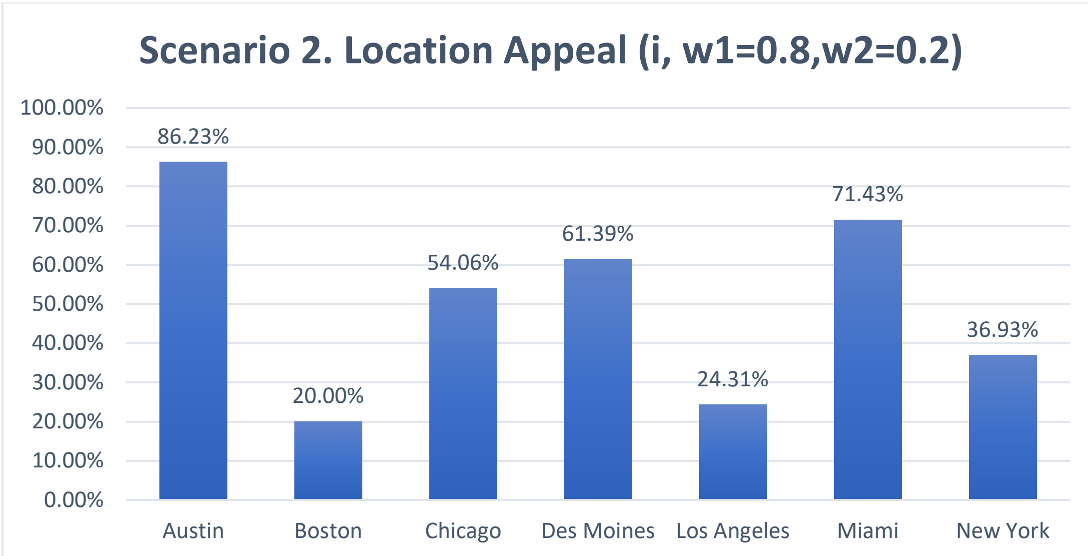

Figure 22. Scenario 2 scores

It can be seen from scenario 2 results that in the event of less efficient vertical farming technology, the city of Austin would still be the best choice to pursue a vertical farming business venture. We could also see the that top three choices are still the same. All in all, the system's evaluation gains confidence as the results remain consistent in this sensitivity analysis scenario.

5.3.3 Overall Confidence in the System – Validation 1

Considering the two sensitivity analysis scenarios, the confidence level of the system decision is solid. The system's initial results seem unphased during both scenarios. In other words, the system will provide robust evaluations that would still apply in the event of possible estimation errors or simply implementing a vertical farming business with different characteristics than the system's benchmark. This observation is great news for the system from a validation standpoint as it shows the evaluation process to be consistent in the event of a possible change in the technology state of the industry. So, under the circumstances of assessing a vertical farming business which deals with a young, volatile industry, lacking public data, the confidence level in the system's results are shown to be very high based on this experiment.

5.4 Impact of Stakeholder Preferences

In this section, we introduce another test to validate and increase the confidence level in the system's proposed decision using stakeholder preferences. Then we examine the effect of stakeholder preferences on the system's evaluation on the broad scale.

5.4.1 The Equal Preferences Scenario – Validation 2

Let us imagine a stakeholder that is not quite sure about his/her preferences regarding profit margin and risk aversion (w1,w2) used in the system. Or perhaps the stakeholder that knows he/she would prefer profit margins over risk aversion but would still like to see what the decision would like in another scenario for reassurance. For this case, let us define a 50-50 scenario, which can be a nice addition to a stakeholder's initial weight preferences. This would help validate the system results, given similar evaluation outcomes. In this scenario, the system assumes an equal importance weight distribution among the risk and profit margin indicators. Figure 23 illustrates the system results under the 50-50 scenario.

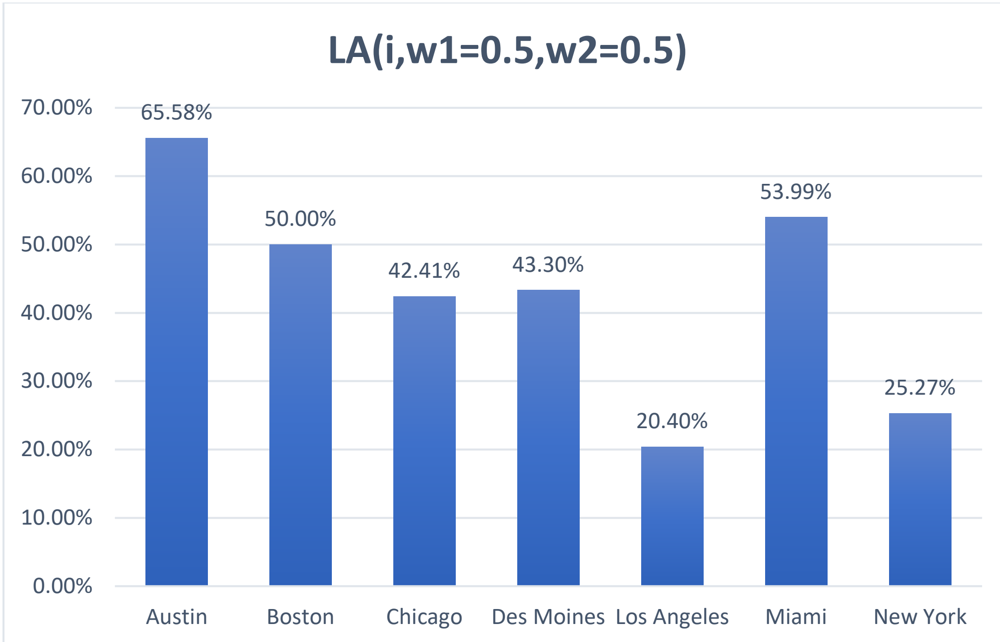

Figure 23. LA(i) for w1=0,5, w2=0.5

The results provided in Figure 23 and Table 14 take another reassuring step towards validating the system's initial suggestion. We can see that Austin would still be the best location alternative even if the stakeholder was more risk aversive than initially thought. We could also observe that Miami is still the second-best alternative. Des Moines appeal drops a rank in this experiment possibly due to its favorable environmental risk conditions for traditional farming.

Table 14. Comparing LA(i) results with two different w1, w2 values

City Name	LA(i, w1=0.8,w2=0.2)	LA(i, w1=0.5,w2=0.5)
Austin	86.23%	65.58%
Boston	20.00%	50%
Chicago	54%	42.41%
Des Moines	60.3%	43.30%
Los Angeles	26.27%	20.24%
Miami	71.06%	53.99%
New York	40.43%	25.75%

5.4.2 Impact of Stakeholder Preferences on a Broad Scale

In this segment, the system is run for a range of profit potential and risk preferences (w1, w2) to illustrate the impact of a decision maker's preference on the alternative assessment.

Figure 24 illustrates the alternative evaluation scores along with the w1, w2 spectrum. It can be seen that our initial favorites, Austin and Miami, appear to be the best alternatives throughout most of the spectrum. We can also observe that whenever almost all importance weight is put on risk aversion, which would be somewhat irrational, Boston would gain relatively high scores due to its high insurance rate.

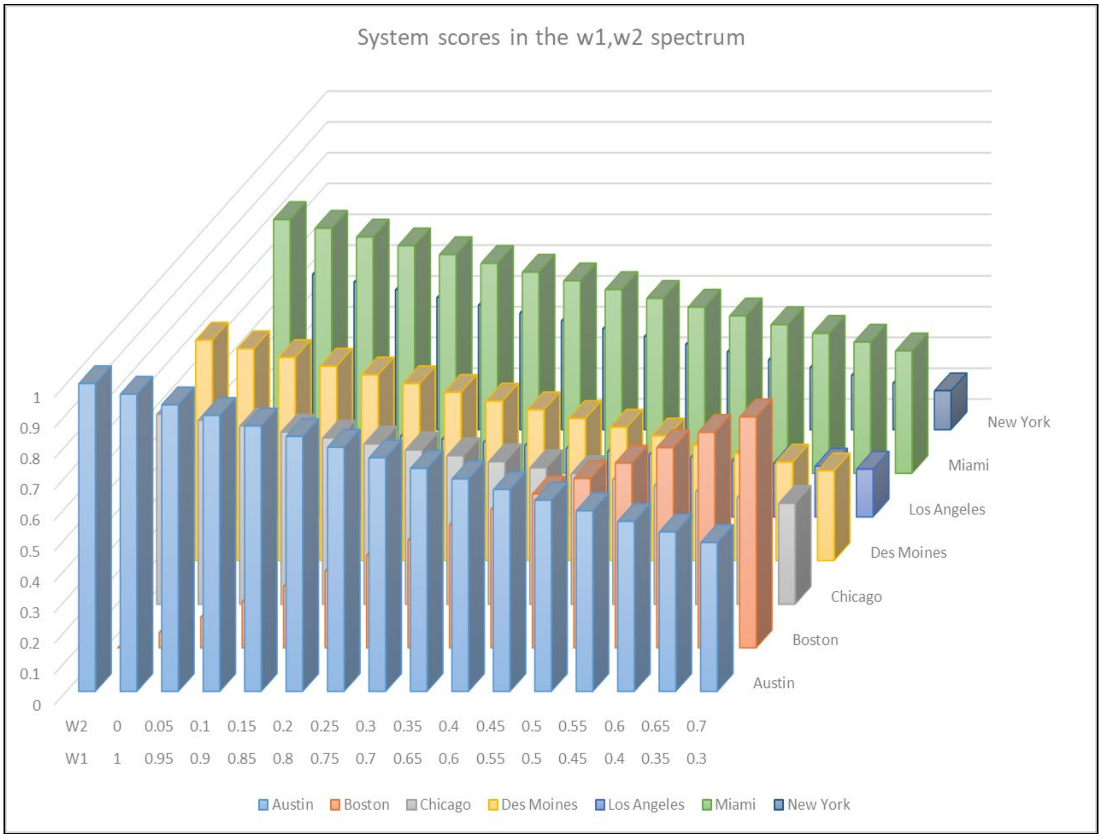

Figure 24. System scoring in the w1, w2 spectrum

5.5 Extreme Cases– Validation 3

In this segment, we seek to analyze two extreme location alternatives to test the boundaries of the system. This analysis seeks to investigate the system's case for two hypothetical location alternatives that are, in theory, the most desirable and the least desirable places to implement a vertical farming business, respectively. Of course, we would expect a robust system to recognize the extremes cases and evaluate them accordingly. Let us define Vertical Farming Paradise and Vertical Farming Purgatory as follows:

Vertical Farming Paradise would have qualities that embolden vertical farming's advantages to minimize its flaws. This hypothetical location would consequently have extremely low energy and labor rates along with very high water and land rates. In addition, this Vertical Farming Paradise would have extreme environmental uncertainties that would make its insurance rates that do not benefit from any government subsidies extremely high. This paradise would also have high market rates for produced goods.

Vertical Farming Purgatory would possess qualities that would magnify vertical farming's flaws while making its advantages irrelevant. This hypothetical location would subsequently have extremely high energy and labor rates along with negligible land and water rates. Not to mention that this Vertical Farming Purgatory would benefit from a long lasting favorable environmental condition. Consequently, the insurance rates would be very low in this location. Not the mention that federal subsidies would cover almost all the insurance rate. This purgatory would also have low market rates for the produced goods. The extreme locations' assumed regional rates are illustrated in Table 15.

Table 15.Extreme alternative location data

City Name	Vertical Farming Paradise	Vertical Farming Purgatory
Median Farm Labor (USD/Hour)	1	100
Energy rate (USD/KwH)	0.005	1
Land rate (USD/Acre/m)	1000	3
Water Price (USD/L)	0.1	0.00001
Regional Price (USD/Head)	10	1.2
Insurance Rate (USD/Acre/y)	700	5
Insurance Subsidy (%	0%	95%
Lettuce (USD/head)	5	1

Figure 25 shows the system evaluation after adding Vertical Farming Paradise and Purgatory to the list of our alternatives. We can see that the system successfully recognizes the extreme alternatives as the best and worst location to implement vertical farming. We could also see that the system successfully recognizes Austin as the best and Miami as the second best non-extreme alternative. This is another reassuring observation for the system. That said, extreme alternatives would negatively skew the scale of the assessment done on other alternatives. This is shown in Figure 25 by the compressed range of LA values for the non-extreme alternatives. Hence, if a stakeholder seeks to examine the second best alternative in the presence of extreme locations, it would be recommended to remove the extreme locations from the alternative list first.

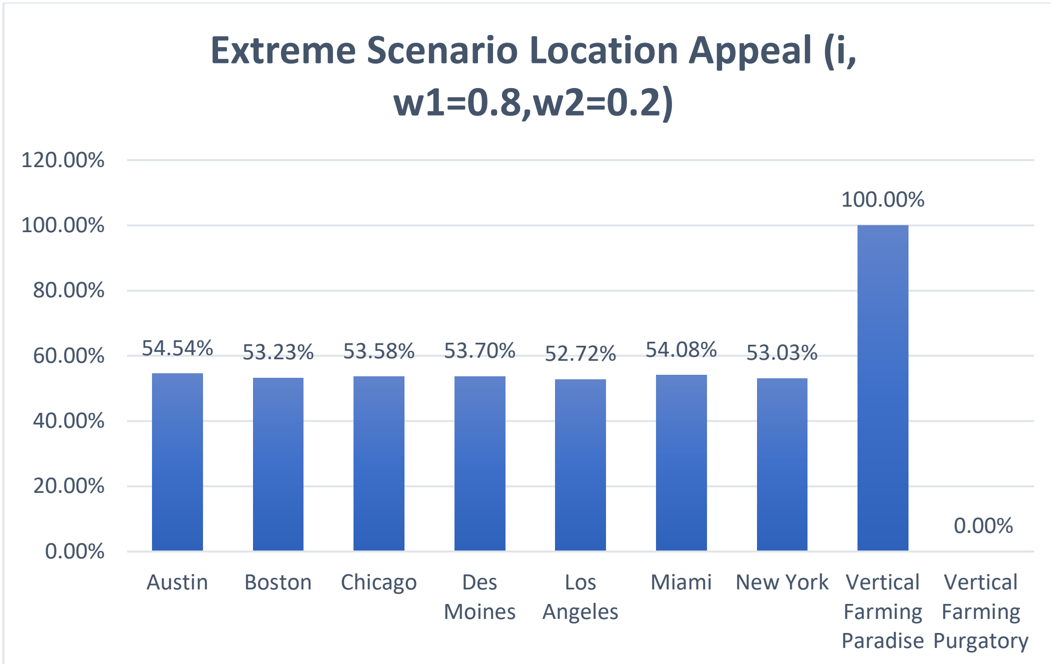

Figure 25. Extreme alternative evaluation

5.6 Validation

As discussed before the vertical farming industry is fairly young, and none of the active producers are publicly traded. Moreover, very few scholars have focused on the economic prospect and business applications of vertical farming. Therefore, the lack of data and similar projects make validating the system results very challenging. In an ideal world, we would have access to two years' worth of data on seven similar vertical farming operations that have been operating in our seven location alternatives. But that is not the world we live in. This would be the case for any new research field that has to start from a more uncertain ground. That said, this study validates the system results in four major steps:

Production Technology Sensitivity Test (5.3.2): It was observed that the system would provide fairly robust results under possible errors in estimating industry benchmarks or implementing superior or inferior forms of vertical farming technology by a stakeholder.

This behavior could support the argument that Austin, for instance, would be the best location alternative within a wide range of vertical farming operating technology.

Equal Stakeholder Preferences Test (5.4.1) : This experiment increased the confidence in the system's evaluation by illustrating to a stakeholder that the suggested alternative would remain true to his/her case to a certain degree even if the stakeholder was more risk aversive.

Extreme Location Alternative Test (5.5): This experiment tested the systems evaluation performance in two extreme locations. The system successfully identified and ranked extreme locations, respectively.

In Line with Existing Understanding of Vertical Farming: The system's performance is fairly in line with the current understanding of vertical farming operations. Vertical farming is commonly known as energy and labor-intensive, risk aversive, space, and water-saving. The system results seem to support all of the mentioned facts commonly known about vertical farming.

All in all, we can argue that considering the information accessible to us for validation in this field of study, there is a strong case to support the validation of the system's performance.

5.7 Future of Vertical Farming

In this section, we seek to gain some perspective into the future of the vertical farming industry by looking into both the production costs and risk factors.

5.7.1 The Profit Margin Aspect

Even with its technological progression, it is commonly known that vertical farming, although it may be able to turn a profit by producing some crops, is still considerably more expensive than traditional farming. To gain a better perspective, average production costs are calculated for the seven location alternatives that were examined in the case study. Figure 26 illustrates the average values associated with different production costs of both farming practices.

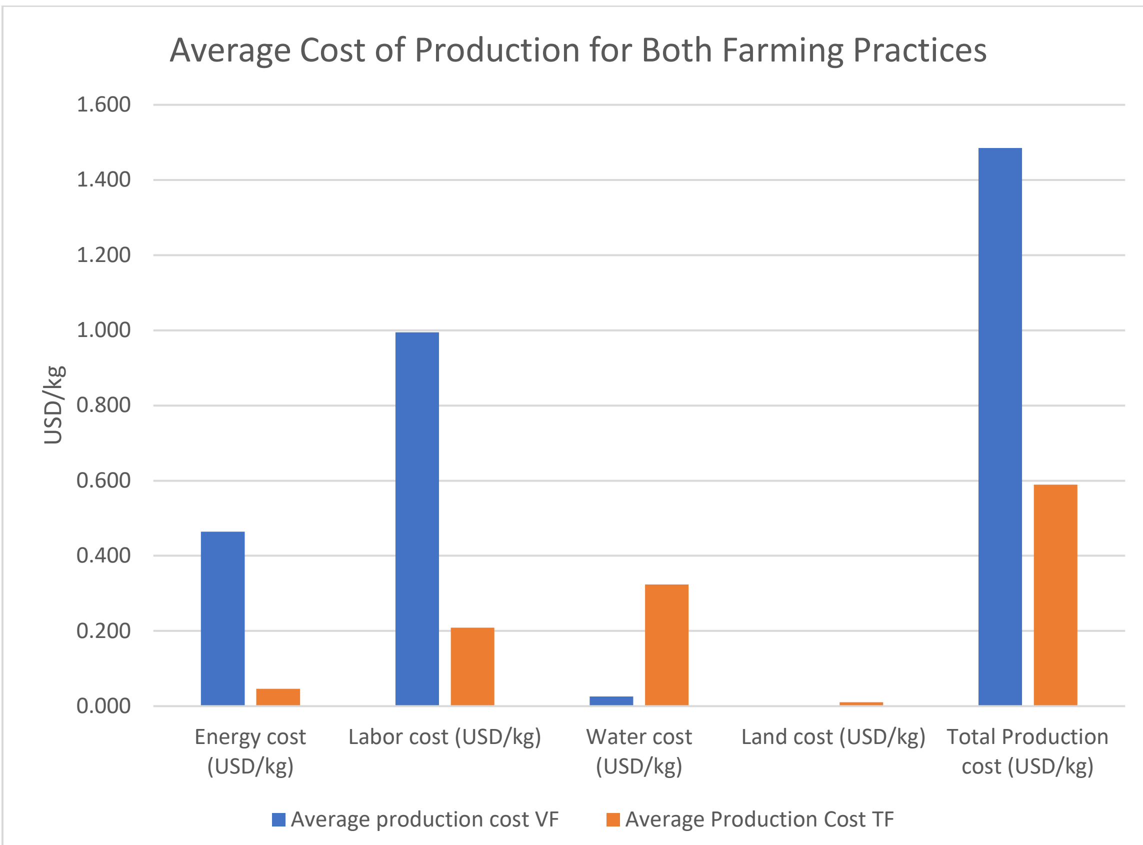

Figure 26. Average production cost per unit for both farming practices

It can be seen that spending savings are very slim in land and water costs, where vertical farming holds the advantage. On the other hand, extra spending is considerable in energy and labor costs, where vertical farming is at a disadvantage. We should also have in mind that this gap was only estimated for lettuce production, and it would be a lot bigger if we were discussing other crops such as tomato or rice. Now even by considering a premium quality product state for vertical farming, the industry still has to close this considerable production cost gap somehow if it aims to become the mainstream form of practice. Here a few factors that might help vertical farming's case in the future are discussed.

Automation: It can be seen that vertical farming is in a vast disadvantage when it comes to labor costs. But the world is moving towards more automation and that might help vertical farming's cost efficiency prospect.

Energy Efficiency Technology: Vertical farming currently chooses to pay for electricity instead of using sun as a free source of energy and that puts the practice at a huge cost disadvantage. Introducing new technologies that would both reduce vertical farming's energy consumption and provide a way to make use of that free solar energy could help the industry in the future.

Water Importance: The planet is facing a global water crisis (Houngbo., 2018) and water prices have been consistently rising over the past few years (circleofblue, 2020). But the water prices, as of now, are still too low to encourage vertical farming's minimal water usage advantage and make a significant difference in the cost of production comparisons. Speculations about pricing future water rates are better left to economists with expertise in that area. However, the speculation that water will somehow become more valuable in the future is one commonly agreed upon. If that is the case, it would greatly favor vertical farming practice.

More Valuable Land: One of the main features of vertical farming is saving space. If fertile land prices happened to increase in the future, whether due to population growth or legislation preventing deforestation, that would heavily favor vertical farming over the traditional practice.

5.7.2 The Risk Aversion Aspect

One of the main advantages of vertical farming is the risk aversion aspect, which was introduced to the system as a separate decision factor. However, we should bear in mind that due to current low insurance rates and government subsidies in the US, the average insurance paid by a traditional farmer for growing a kg of lettuce could be as low as 0.004 $. One could see why this low figure might hinder possible risk aversive incentives related to vertical farming. There is a large body of literature pointing out some of the flaws in the current crop insurance program in the US (SMITH, 2013), (XIAODONG DU, 2016), (Sumner, 2012), (United States Department of Agriculture Economic Research Service, 2019). Some of these issues include the program providing more subsidies to big farmers compared to small farmers using tax payer money, incentivizing riskier farming practices, becoming more costly over time with increased insurance rates, encouraging non environmentally friendly farming practices, and the program having costlier future projections due to global climate change. Now, will these insurance subsidies discourage stakeholders from taking part in vertical farming? Possibly, but that is a question better left for agricultural economists to answer. Plus, considering the current high production costs and low variety of produced crops, the insurance and subsidy rates are probably not the priority problem blocking vertical farming's progress. Still, if at any point in the future, the insurance rates increase due to global climate change or USDA's choice to reduce insurance subsidies, that would probably favor the vertical farming industry.

5.8 Chapter Conclusion

This chapter utilizes the Decision Support System proposed in chapter 4 to conduct a case study with regards to the relative appeal of implementing vertical farming in seven distinct location alternatives. Then a series of validation tests are carried out to check the robustness and validity of the results generated by the system. Finally, the results of the case study are assessed to gain some insight into the future of the vertical farming industry. The case study illustrates that the city of Austin would be the relatively best alternative to pursue a vertical farming business. Miami and Des Moines are shown to be other attractive alternatives; the system confirms this indication through a series of sensitivity analyses and validation tests.

To the best of our knowledge, this the first time, a case study of this scale has been conducted to evaluate vertical farming from a business perspective. For future work, it would be interesting to increase the number of location alternatives to broaden our understanding of vertical farming's business prospects. It could also be interesting to introduce other market evaluation metrics such as regional consumer income, regional population, regional demand, etc. Moreover, the current system can be modified to study the impact of future energy, land, and water pricing on vertical farming appeal. Assessing the relative environmental hazards done by both practices in each location alternative can be quite valuable as well.

6 CONCLUSION AND FUTURE WORK

There are various problems associated with our conventional practice of farming. In the past few years alone, agriculture has been responsible for a million square kilometers of deforestation. The world is facing a water crisis, and farming is responsible for using 80% of its freshwater. The prospect of global climate change is projecting a much riskier future to the practice of conventional farming due to more pesticide incidences, weather uncertainties, changing rain patterns, and more frequent climate extremes. One could argue that these alarming problems might someday be treated as more imminent as the population grows, less fertile land becomes available, the effects of global climate change become more apparent, and the societal concerns for sustainability grows. Some could argue that when the costs associated with the mentioned issues are fully realized in the market, it would be a lot more expensive to practice conventional farming. Not to mentioned that it is more likely that the post Covid world would have an increased desire for having locally grown food sources. Perhaps, but we do not know for certain. Either way, the fact is that a new industry of vertical farming businesses has been emerging worldwide in recent years, betting on that future. The global industry previously valued at $3.16 Billion in 2018 is projected to reach a staggering $22.07 Billion by 2026 (Global Market Insights, 2019). There is a lot of effort dedicated to improving the vertical farming production technology, which is important to the industry's growth. That said, considerable growth in any industry would also require ample effort and investments dedicated to developing a better understanding of the field in terms of economics and business. Also, an emerging industry would typically develop a dire need for novel analytics and decision-making tools. However, the focus on these aspects of vertical farming has been oddly limited. Hence, this study's material could prove to help with a dire need in an expanding industry.

This study provides a comprehensive set of models within two general frameworks that can be utilized as a business/economic analytics tool to evaluate vertical farming. Moreover, the study proposes a flexible Decision Support System for choosing the best location alternatives of vertical farming in a competitive market place, which, to the best of our knowledge, is the first Decision Support System designed for vertical farming location-based suitability analysis. As the vertical farming industry grows, it will attract more and more interested parties in its ecosystem. They could be investors, policymakers, analysts, scholars, etc. These interested parties will increase the demand for more knowledge-based insights and more analytics tools to examine vertical farming. Our proposed system is flexible enough to help every one of them in some way or form. They could evaluate their investment alternatives. They could gain insights about the future of the industry in various locations. They could modify the system to gain insights about how a new vertical farming technology would work in the market. They could acquire the system's help in planning a vertical farming business expansion. The case study conducted in chapter 5 showed us a glimpse of the potential insights we can acquire utilizing the proposed system. Still, no similar studies have been done examining the prospect of vertical farming applications within the US on this scale. All in all, the contents of this study could prove to be quite helpful in this relatively untouched field of study in an emerging industry that has a growing need for it. There is still much more work to be done concerning the economic and business side of vertical farming. We hope that this study would help contribute to future endeavors in this field.

For future work, we could seek to improve the Decision Support System by developing a fully automated and interactive web-based system for future work. Introducing more evaluation and validation algorithms as the system acquires more data can be another task for this system's future. Also, introducing a decision factor under the title of "environmental hazards" as introduced in chapter 2 could complement this study, should the required data be accessible. It would also be interesting to conduct a case study for a much larger set of location alternatives. We could introduce other market evaluation metrics such as regional consumer income, regional population, regional demand, etc. Moreover, the current system can be modified to study the impact of future energy, land, and water pricing on vertical farming appeal. Finally, if enough data is gathered, one can look to introduce elements of probability into the system and convert the deterministic decision-making system into a stochastic one.

APPENDIX SECTION

Appendix A: Codes

```
Import pandas
import cpi
#reading and mapping the initial data using the pandas
df_raw = pd.read_csv (r'C:\Users\faraz\Desktop\thesis\data\PythonReadyData.csv')
#61871 rows in raw data
#1 removing the rows with zero or negligable total premium
df_1= df_raw[df_raw['Total Prem ($)'] >5 ]
df_1=df_1.reset_index(drop=True)    #55260 rows
#dropping the 'Addnl Subsidy ($)' column --- 23 rows
df_1.drop(['Addnl Subsidy ($)','Companion/Endorsed Acres','EFA Prem Discount ($)','State Subsidy
($)','Earn Prem Rate','Loss Ratio'], axis=1)
# df_1.drop(['Delivery Type Code'], axis=1)
# df_1.drop(['Companion/Endorsed Acres'], axis=1)
# df_1.drop(['EFA Prem Discount ($)'], axis=1)
# df_1.drop(['State Subsidy ($)'], axis=1)
# df_1.drop(['Earn Prem Rate'], axis=1)
# df_1.drop(['Loss Ratio'], axis=1)
#converting different types of tabacco to a single entity
df_1.replace({'Commodity Name': {'BURLEY TOBACCO':

'TOBACCO', 'CIGAR BINDER TOBACCO': 'TOBACCO', '

CIGAR FILLER TOBACCO':'TOBACCO', 'CIGAR WRAPPER TOBACCO':'TOBACCO' }})
#df_1['Commodity Name'].__contains__('BURLEY TOBACCO')  check to see if it worked

print(df_1['Liabilities ($)'].dtype)

#Adjusting for inflation

df_adjusted = df_1

df_adjusted ['Liabilities ($)'] = df_adjusted.apply(lambda x: cpi.inflate(x['Liabilities ($)'],
x['Commodity Year']), axis=1)
df_adjusted ['Indemnity ($)'] = df_adjusted.apply(lambda x: cpi.inflate(x['Indemnity ($)'],
x['Commodity Year']), axis=1)
df_adjusted ['Subsidy ($)'] = df_adjusted.apply(lambda x: cpi.inflate(x['Subsidy ($)'], x['Commodity
Year']), axis=1)
df_adjusted ['Total Prem ($)'] = df_adjusted.apply(lambda x: cpi.inflate(x['Total Prem ($)'],
x['Commodity Year']), axis=1)
```

Code 2. insurance data

```
#Generating a Yearly aggregate numbers table
group=df_adjusted.groupby('Commodity Year')

YearlyTable= group.agg({'Liabilities ($)':'sum', 'Indemnity ($)':'sum', 'Subsidy
($)':'sum','Total Prem ($)':'sum','Policies Earning Prem':'sum','Policies
Indemnified':'sum','Units Earning Prem':'sum', 'Units Indemnified':'sum','Quantity':'sum'})

YearlyTable=pd.DataFrame(YearlyTable)

YearlyTable.to_csv('YearlyTable.csv')

group2=df_adjusted.groupby(['Commodity Year','State Abbrv'])

YearStateTable= group2.agg({'Liabilities ($)':'sum', 'Indemnity ($)':'sum', 'Subsidy
($)':'sum','Total Prem ($)':'sum','Policies Earning Prem':'sum','Policies
Indemnified':'sum','Units Earning Prem':'sum', 'Units Indemnified':'sum','Quantity':'sum'})
YearCountyTable.to_csv('YearCountyTable.csv')
```

Code 3. Acquiring risk and insurance data

Appendix B: Comprehensive Worksheet

In this segment extensive work sheets for each of the conducted case study are included.

Table 16. Overall extensive worksheet

City Name	Austin	Boston	Chicago	Des Moines	Los Angeles	Miami	New York
Stat initial	TX	MA	IL	IO	CA	FL	NY
Median FarmLabor Cost (per ManH	11.61	17.36	16.6	14.6	16	12.67	15.6
Labor Cost (VF)USD/kg	0.774	1.157333	1.106667	0.973333	1.066667	0.844667	1.04
Labor cost (TF)USD/kg	0.16254	0.24304	0.2324	0.2044	0.224	0.17738	0.2184
Energy rate per KWH commercial USD/KwH	0.078	0.17	0.09	0.0986	0.16	0.094	0.133
Energy Rate Industrial USD/KwH	0.0539	0.139	0.0663	0.0619	0.12	0.0717	0.0524
Energy Cost per kg (VF) (Industrial) USD/kg	0.309925	0.79925	0.381225	0.355925	0.69	0.412275	0.3013
Energy Cost Commercial (VF) USD/kg	0.4485	0.9775	0.5175	0.56695	0.92	0.5405	0.76475
Energy Cost Industrial TF USD/kg	0.030993	0.079925	0.038123	0.035593	0.069	0.041228	0.03013
Energy Cost Commercial TF USD/kg	0.04485	0.09775	0.05175	0.056695	0.092	0.05405	0.076475
Fertile Land Rent USD/Acre	42.5	88.5	224	230	423	110	66
Fertile Land rent (USD/M2	0.010502	0.021869	0.055352	0.056834	0.104525	0.027182	0.016309

Fertile Land rent per kg(TF) USD/kg	0.002625	0.005467	0.013838	0.014209	0.026131	0.006795	0.004077
Normal land rent USD/Acre	6	35	41	59	13	15.5	26
Normal land rent p m2	0.001483	0.008649	0.010131	0.014579	0.003212	0.00383	0.006425
Normal land rent p kg (vf)	9.88E-06	5.77E-05	6.75E-05	9.72E-05	2.14E-05	2.55E-05	4.28E-05
Water Price per liter	0.001208	0.00145	0.0012	0.001	0.0016	0.0012	0.001413
Water Cost (VF) USD/kg	0.024167	0.029	0.024	0.02	0.032	0.024	0.028252
Water Cost TF USD/kg	0.302083	0.3625	0.3	0.25	0.4	0.3	0.353147
VF V Cost USD/kg	1.108102	1.985641	1.511959	1.349356	1.788688	1.280967	1.369595
TF V Cost USD/kg	0.498241	0.690932	0.58436	0.504201	0.719131	0.525403	0.605754
Regional Price per head	1.99	1.79	1.99	1.99	1.79	1.99	1.49
Regional lettuce Price per kg	4.522727	4.068182	4.522727	4.522727	4.068182	4.522727	3.386364
PV%	0.754993	0.511909	0.665697	0.70165	0.560322	0.716771	0.595556
PT%	0.889836	0.830162	0.870795	0.888518	0.82323	0.883831	0.821119
PA	-0.13484	-0.31825	-0.2051	-0.18687	-0.26291	-0.16706	-0.22556

PDI (Scaled PA)	1	0	0.616956	0.716345	0.301755	0.824349	0.505367
Subsidy%	0.7	0.63	0.57	0.54	0.59	0.63	0.7
Premium per Acre	74	146	43	32	31	53	26
RA	22.2	54.02	18.49	14.72	12.71	19.61	7.8
RDI	0.311553	1	0.231285	0.149719	0.106231	0.255517	0
LA(i, w1=0.8,w2=0.2)	0.862311	0.2	0.539822	0.60302	0.262651	0.710583	0.404294
LA(i,w1=0.5,w2=0.5)	0.655777	0.5	0.42412	0.433032	0.203993	0.539933	0.252684

Table 17. Scenario 1 extensive worksheet

City Name	Austin	Boston	Chicago	Des Moines	Los Angeles	Miami	New York
Stat Initial	TX	MA	IL	IO	CA	FL	NY
Median Farm Labor Cost (per ManH	11.61	17.36	16.6	14.6	16	12.67	15.6
Labor Cost (VF)USD/kg	0.5805	0.868	0.83	0.73	0.8	0.6335	0.78
Labor cost (TF)USD/kg	0.16254	0.24304	0.2324	0.2044	0.224	0.17738	0.2184
Energy rate per KWH commercial USD/KwH	0.078	0.17	0.09	0.0986	0.16	0.094	0.133
Energy Rate Industrial USD/KwH	0.0539	0.139	0.0663	0.0619	0.12	0.0717	0.0524

Energy Cost per kg (VF) (Industrial) USD/kg	0.232309	0.59909	0.285753	0.266789	0.5172	0.309027	0.225844
Energy Cost Commercial (VF) USD/kg	0.33618	0.7327	0.3879	0.424966	0.6896	0.40514	0.57323
Energy Cost Industrial TF USD/kg	0.023231	0.059909	0.028575	0.026679	0.05172	0.030903	0.022584
Energy Cost Commercial TF USD/kg	0.033618	0.07327	0.03879	0.042497	0.06896	0.040514	0.057323
Fertile Land Rent USD/Acre	42.5	88.5	224	230	423	110	66
Fertile Land rent (USD/M2	0.010502	0.021869	0.055352	0.056834	0.104525	0.027182	0.016309
Fertile Land rent per kg(TF) USD/kg	0.002625	0.005467	0.013838	0.014209	0.026131	0.006795	0.004077
Normal land rent USD/Acre	6	35	41	59	13	15.5	26
Normal land rent p m2	0.001483	0.008649	0.010131	0.014579	0.003212	0.00383	0.006425
Normal land rent p kg (vf)	7.9E-06	4.61E-05	5.4E-05	7.76E-05	1.71E-05	2.04E-05	3.42E-05
Water Price per liter	0.001208	0.00145	0.0012	0.001	0.0016	0.0012	0.001413
Water Cost (VF) USD/kg	0.018125	0.02175	0.018	0.015	0.024	0.018	0.021189
Water Cost TF USD/kg	0.302083	0.3625	0.3	0.25	0.4	0.3	0.353147
VF V Cost USD/kg	0.830942	1.488886	1.133807	1.011867	1.341217	0.960547	1.027067

TF V Cost USD/kg	0.49048	0.670916	0.574813	0.495287	0.701851	0.515078	0.598209
Regional Price per head	1.99	1.79	1.99	1.99	1.79	1.99	1.49
Regional lettuce Price per kg	4.522727	4.068182	4.522727	4.522727	4.068182	4.522727	3.386364
PV%	0.816274	0.634017	0.749309	0.776271	0.670315	0.787618	0.696705
PT%	0.891552	0.835082	0.872906	0.890489	0.827478	0.886113	0.823348
PA	-0.07528	-0.20107	-0.1236	-0.11422	-0.15716	-0.0985	-0.12664
PDI (Scaled PA)	1	0	0.615871	0.690426	0.349024	0.815421	0.591655
Subsidy%	0.7	0.63	0.57	0.54	0.59	0.63	0.7
Premium per Acre	74	146	43	32	31	53	26
RA	22.2	54.02	18.49	14.72	12.71	19.61	7.8
RDI	0.311553	1	0.231285	0.149719	0.106231	0.255517	0
LA(i, w1=0.8,w2=0.2)	0.862311	0.2	0.538954	0.582284	0.300465	0.70344	0.473324
LA(i,w1=0.5,w2=0.5)	0.655777	0.5	0.423578	0.420072	0.227627	0.535469	0.295827

Table 18. Scenario 2 extensive work sheet

City Name	Austin	Boston	Chicago	Des Moines	Los Angeles	Miami	New York
Stat Initial	TX	MA	IL	IO	CA	FL	NY
Median Farm Labor Cost (per ManH	11.61	17.36	16.6	14.6	16	12.67	15.6
Labor Cost (VF)USD/kg	0.96363	1.44088	1.3778	1.2118	1.328	1.05161	1.2948
Labor cost (TF)USD/kg	0.16254	0.24304	0.2324	0.2044	0.224	0.17738	0.2184
Energy rate per KWH commercial USD/KwH	0.078	0.17	0.09	0.0986	0.16	0.094	0.133
Energy Rate Industrial USD/KwH	0.0539	0.139	0.0663	0.0619	0.12	0.0717	0.0524
Energy Cost per kg (VF) (Industrial) USD/kg	0.387002	0.99802	0.476034	0.444442	0.8616	0.514806	0.376232
Energy Cost Commercial (VF) USD/kg	0.56004	1.2206	0.6462	0.707948	1.1488	0.67492	0.95494
Energy Cost Industrial TF USD/kg	0.0387	0.099802	0.047603	0.044444	0.08616	0.051481	0.037623
Energy Cost Commercial TF USD/kg	0.056004	0.12206	0.06462	0.070795	0.11488	0.067492	0.095494
Fertile Land Rent USD/Acre	42.5	88.5	224	230	423	110	66
Fertile Land rent (USD/M2	0.010502	0.021869	0.055352	0.056834	0.104525	0.027182	0.016309
Fertile Land rent per kg(TF) USD/kg	0.002625	0.005467	0.013838	0.014209	0.026131	0.006795	0.004077
Normal land rent USD/Acre	6	35	41	59	13	15.5	26
Normal land rent p m2	0.001483	0.008649	0.010131	0.014579	0.003212	0.00383	0.006425

Normal land rent p kg (vf)	1.32E-05	7.72E-05	9.05E-05	0.00013	2.87E-05	3.42E-05	5.74E-05
Water Price per liter	0.001208	0.00145	0.0012	0.001	0.0016	0.0012	0.001413
Water Cost (VF) USD/kg	0.030208	0.03625	0.03	0.025	0.04	0.03	0.035315
Water Cost TF USD/kg	0.302083	0.3625	0.3	0.25	0.4	0.3	0.353147
VF V Cost USD/kg	1.380854	2.475227	1.883924	1.681372	2.229629	1.59645	1.706404
TF V Cost USD/kg	0.505949	0.710809	0.593841	0.513053	0.736291	0.535656	0.613248
Regional Price per head	1.99	1.79	1.99	1.99	1.79	1.99	1.49
Regional lettuce Price per kg	4.522727	4.068182	4.522727	4.522727	4.068182	4.522727	3.386364
PV%	0.694686	0.391564	0.583454	0.628239	0.451935	0.647016	0.496095
PT%	0.888132	0.825276	0.868698	0.886561	0.819012	0.881563	0.818907
PA	-0.19345	-0.43371	-0.28524	-0.25832	-0.36708	-0.23455	-0.32281
PDI (Scaled PA)	1	0	0.61793	0.729983	0.277336	0.828934	0.461574
Subsidy%	0.7	0.63	0.57	0.54	0.59	0.63	0.7
Premium per Acre	74	146	43	32	31	53	26
RA	22.2	54.02	18.49	14.72	12.71	19.61	7.8

RDI	0.311553	1	0.231285	0.149719	0.106231	0.255517	0
LA(i, w1=0.8,w2=0.2)	0.862311	0.2	0.540601	0.613931	0.243115	0.714251	0.36926
LA(i,w1=0.5,w2=0.5)	0.655777	0.5	0.424607	0.439851	0.191784	0.542226	0.230787

Table 19. Extreme case extensive worksheet

City Name	Austin	Boston	Chicago	Des Moines	Los Angeles	Miami	New York	Vertical Farming Paradis	Vertical Farming Purgatory
Stat initial	TX	MA	IL	IO	CA	FL	NY		
Median Farm Labor Cost (per ManH)	11.61	17.36	16.6	14.6	16	12.67	15.6	1	100
Labor Cost (VF)USD/kg	0.774	1.157333	1.106667	0.973333	1.066667	0.844667	1.04	0.066667	6.666667
Labor cost (TF)USD/kg	0.16254	0.24304	0.2324	0.2044	0.224	0.17738	0.2184	0.014	1.4
Energy rate per KWH commercial USD/KwH	0.078	0.17	0.09	0.0986	0.16	0.094	0.133	0.008	1
Energy Rate Industrial USD/KwH	0.0539	0.139	0.0663	0.0619	0.12	0.0717	0.0524	0.005	1
Energy Cost per kg (VF) (Industrial) USD/kg	0.309925	0.79925	0.381225	0.355925	0.69	0.412275	0.3013	0.02875	5.75

Energy Cost Commercial (VF) USD/kg	0.4485	0.9775	0.5175	0.56695	0.92	0.5405	0.76475	0.046	5.75
Energy Cost Industrial TF USD/kg	0.030993	0.079925	0.038123	0.035593	0.069	0.041228	0.03013	0.002875	0.575
Energy Cost Commercial TF USD/kg	0.04485	0.09775	0.05175	0.056695	0.092	0.05405	0.076475	0.0046	0.575
Fertile Land Rent USD/Acre	42.5	88.5	224	230	423	110	66	1000	3
Fertile Land rent (USD/M2	0.010502	0.021869	0.055352	0.056834	0.104525	0.027182	0.016309	0.247105	0.000741
Fertile Land rent per kg(TF) USD/kg	0.002625	0.005467	0.013838	0.014209	0.026131	0.006795	0.004077	0.061776	0.000185
Normal land rent USD/Acre	6	35	41	59	13	15.5	26	60	3
Normal land rent p m2	0.001483	0.008649	0.010131	0.014579	0.003212	0.00383	0.006425	0.014826	0.000741
Normal land rent p kg (vf)	9.88E-06	5.77E-05	6.75E-05	9.72E-05	2.14E-05	2.55E-05	4.28E-05	9.88E-05	4.94E-06
Water Price per liter	0.001208	0.00145	0.0012	0.001	0.0016	0.0012	0.001413	0.1	0.00001
Water Cost (VF) USD/kg	0.024167	0.029	0.024	0.02	0.032	0.024	0.028252	2	0.0002
Water Cost TF USD/kg	0.302083	0.3625	0.3	0.25	0.4	0.3	0.353147	25	0.0025
VF V Cost USD/kg	1.108102	1.985641	1.511959	1.349356	1.788688	1.280967	1.369595	2.095516	12.41687

TF V Cost USD/kg	0.498241	0.690932	0.58436	0.504201	0.719131	0.525403	0.605754	25.07865	1.977685
Regional Price per head	1.99	1.79	1.99	1.99	1.79	1.99	1.49	5	1
Regional lettuce Price per kg	4.522727	4.068182	4.522727	4.522727	4.068182	4.522727	3.386364	11.36364	2.272727
PV%	0.754993	0.511909	0.665697	0.70165	0.560322	0.716771	0.595556	0.815595	-4.46342
PT%	0.889836	0.830162	0.870795	0.888518	0.82323	0.883831	0.821119	-1.20692	0.129818
PA	-0.13484	-0.31825	-0.2051	-0.18687	-0.26291	-0.16706	-0.22556	2.022516	-4.59324
PDI (Scaled PA)	0.673906	0.646183	0.663287	0.666042	0.654548	0.669036	0.660193	1	0
Subsidy%	0.7	0.63	0.57	0.54	0.59	0.63	0.7	0	0.95
Premium per Acre	74	120	43	32	31	53	26	700	5
RA	22.2	44.4	18.49	14.72	12.71	19.61	7.8	700	0.25
RDI	0.031368	0.063094	0.026066	0.020679	0.017806	0.027667	0.01079	1	0
LA(i, w1=0.8,w2=0.2)	0.545398	0.529565	0.535843	0.536969	0.5272	0.540762	0.530312	1	0
LA(i,w1=0.5,w2=0.5)	0.352637	0.354638	0.344677	0.34336	0.336177	0.348352	0.335491	1	0

BIBLIOGRAPHY

Aerofarms. (2020). Retrieved from https://aerofarms.com/

allardo M, S. R. (1996). Crop growth and water use model for lettuce. Journal of irrigation and drainage engineering.

Andrew M. Beacham, L. H. (2019). Vertical farming: a summary of approaches to growing skywards. The Journal of Horticultural Science and Biotechnology .

Anirudh Garg, R. B. (2014). Recent trends in agriculture: vertical farming and organic farming.

Barbosa, G. G. (2015). Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. conventional agricultural methods. International journal of environmental research and public health.

Besthorn, F. H. (2012). Vertical Farming: Social Work and Sustainable Urban Agriculture in an Age of Global Food Crises.

cambridgehok. (2020). cambridgehok. Retrieved from cambridgehok: https://cambridgehok.co.uk/vertical-farming/news/how-much-does-vertical-farming-cost

Chirantan Banerjee, L. A. (2014). Up, Up and Away! The Economics of Vertical Farming. Journal of Agricultural Studies.

Choez, W. O., Cortázar, M. Q., Cruz, S. H., & Carvache, a. K. (2017). framework for PEST analysis based on neutrosophic cognitive map: case study in a vertical farming. Neutrosophic Sets and Systems, .

Cıceklı, M., & Barlas, N. T. (2014). Transformation of today greenhouses into high technology Vertical Farming Systems for metropolitan regions. Journal of Environmental Protection and Ecology.

circleofblue. (2020). Retrieved from https://www.circleofblue.org/waterpricing/

Coleman, R. (2014). Low-tech innovations in vertical farming: Nairobi, Kenya. Urban Agriculture Magazine.

D. Leite, R. M. (2016). Economic feasibility of implementing the hydroponic system for lettuce with PRONAF resources in Matão-SP.

de França Xavier, J. e. (2018). Economic Viability and Profitability of Lettuce in Hydroponic System Using Different Effluents. Journal of Agricultural Science.

Django. (2020). djangoproject. Retrieved from djangoproject: https://www.djangoproject.com/

Djevic, M. &. (2009). Energy consumption for different greenhouse constructions. Energy, 34(9).

dos Santos, J. D. (2013). Development of a vinasse nutritive solution for hydroponics. Journal of environmental management.

Economic Research Service. (2019). Risk in Agriculture. USDA.

Evergreen- Txstate. (2020). Evergreen . Retrieved from Evergreen: https://www.evergreen.txstate.edu/

FAO. (2020). FAO. Retrieved from https://www.FAO.org

Fatemeh Kalantari, O. M. (2017). Opportunities And Challenges In Sustainability Of Vertical Farming: A Review. Journal of Landscape Ecology.

Fatemeh Kalantari1, a. M. (2017). A Review of Vertical Farming Technology: A Guide for Implementation. Advanced Engineering Forum. Vol. 24. Trans Tech Publications.

Fischetti, M. (2008). Growing Vertical. Scientific American, vol. 18, issue 4, pp. 74-79.

Freight Farms. (2020). Retrieved from https://www.freightfarms.com/

Frieght Farms. (n.d.). Retrieved from https://www.freightfarms.com/

fullbloomgreenhouse. (2019). fullbloomgreenhouse. Retrieved from fullbloomgreenhouse: https://www.fullbloomgreenhouse.com/hydroponic-systems-101/

Galinato, S. a. (2013). Economic profitability of growing lettuce and tomato in western Washington under high tunnel and open-field production systems. HortTechnology.

Gane, C., & Sarson, T. (1977). Structured Systems Analysis. New York: Improved Systems Technologies.

Geography, N. (2018, Feb 28). Retrieved from https://genographic.nationalgeographic.com/development-of-agriculture/}

Global Market Insights . (2019). Vertical Farming Market Size By Product.

Govrenment, U. F. (n.d.). Irrigation Water Use. Retrieved from https://www.usgs.gov/special-topic/water-science-school/science/irrigation-water-use?qt-science_center_objects=0#qt-science_center_objects

Helmer, J. (2019). Is Vertical Farming Here to Stay? Retrieved from igrow: https://www.igrow.news/igrownews/is-vertical-farming-here-to-stay

Houngbo, G. F. (2018). The United Nations world water development report 2018: nature-based solutions for water.

Houngbo., G. F. (2018). The United Nations world water development report .

Hussain, A. R. (2009). The economics of sprinkler irrigation uniformity for lettuce production with in-season rainfall. In Proceedings of the 2009 CIGR International Symposium of the Australian Society for Engineering in Agriculture.

IGrow. (2015). A Leader in The Localization of Agriculture. Retrieved from https://www.igrow.news/: https://www.igrow.news/igrownews/2016/8/29/see-inside-this-vertical-farm-where-65000-pounds-of-lettuce-grow-each-year-in-shipping-containers?rq=KWH

James Clawson, S. R. (1998). Developing a Sterile Environment for Aeroponic Plant Growth. nasa space commercialization center.

james e. rakocy, d. s. (2013). update on tilapia and vegetable production in the. agricultural experiment station , 15.

Jianzhou Gonga, b. Y. (2010). Land suitability evaluation for development using a matter-element model: A case study in Zengcheng, Guangzhou, China. Land Use Policy.

Keen, P. (1980). Decision support systems : a research perspective. Center for Information Systems Research,.

MalekAl-Chalabi. (2015). Vertical farming: Skyscraper sustainability? Sustainable Cities and Society.

McAinsh, D. T. (2016). Vertical farming increases lettuce yield per unit area compared to conventional horizontal hydroponics.

Milius, S. (2017). Worries Grow that Climate Change will Quietly Steal Nutrients from Major Food Crops. Science News Year in Review Nutrition, Climate, Sustainability.

Molin, M. M. (2019). Environmental Assessment of an Urban Vertical and Hydroponic Farming System in Sweden.

NY Department of Labor and Statistics. (2020). NY-stats. Retrieved from https://labor.ny.gov/stats/lswage2.asp#45-0000

R, A. G. (2020.). Recent trends in agriculture: vertical farming and organic farming. Adv Plants Agric.

Service, N. P. (n.d.). Hydroponics: A Better Way to Grow Food. Retrieved from National Park Service: https://www.nps.gov/articles/hydroponics.htm

Smith, B. K. (2013). What Harm Is Done By Subsidizing Crop Insurance?

Smith, P. a. (2014). Climate change 2014: mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Sparks, G. (2011). Database Modelling in UML. Retrieved from Database Modelling in UML: http://www.methodsandtools.com/archive/archive.php?id=9

SPREAD. (2020). Techno Farm. Retrieved from https://spread.co.jp/en/technofarm/

statisticshowto. (2015). statisticshowto. Retrieved from statisticshowto: https://www.statisticshowto.com/normalized/

Sulma Vanessa Souzaa, a. o. (2019). Economic viability for deploying hydroponic system in emerging countries: A differentiated risk adjustment proposal. Land Use Policy.

Sumner, D. A. (2012). Economic & Environmental Effects of Agricultural Insurance Programs. The Conservation Crossroads in Agriculture.

Tasgal, P. (2019). The Economics of Local Vertical and Greenhouse Farming Are Getting Competitive. Retrieved from The Economics of Local Vertical and Greenhouse Farming Are Getting Competitive: https://agfundernews.com/the-economics-of-local-vertical-and-greenhouse-farming-are-getting-competitive.html

Technofarm. (2020). Retrieved from https://technofarm.com/en/

Technofarm innovation. (2020). Technofarm inovation. Retrieved from http://technofarm.com: http://technofarm.com/en/innovation/

Tomkins, K. B. (2017). Future food-production systems: vertical farming.

Toyoka Kozai, G. N. (2020). Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food ...

Toyoki Kozai, K. F. (2016). LED Lighting for Urban Agriculture. Springer.

Trimbo, A. A. (2019). Economic Sustainability Of Indoor Vertical Farming . Escola De Administração De Empresas De São Paulo.

United States Department of Agriculture Economic Research Service. (2019). Climate Change Projected To Increase Cos of the Federal Crop Insurance Program due to Greater Insured Value and Yield Variability. USDA.

urbanagnews. (2020). urbanagnews. Retrieved from https://urbanagnews.com/blog/exclusives/the-quality-standards-for-hydroponic-lettuce/

US Department of Labor and Statistics. (2020). Chicago - stats. Retrieved from https://www.bls.gov/regions/midwest/news-release/occupationalemploymentandwages_chicago.htm

US Department of Labor and Statistics. (2020). Des Moines - stats. Retrieved from https://www.bls.gov/oes/current/oes_ia.htm

US Department of Labor and Statistics. (2020). LA - stats . Retrieved from https://www.bls.gov/regions/west/news-release/occupationalemploymentandwages_losangeles.htm

US Department of Labor and Statistics. (2020). Miami-stats. Retrieved from https://www.bls.gov/regions/southeast/news-release/occupationalemploymentandwages_miami.htm

US Department of Labor and Statistics. (2020). Stats- Boston. Retrieved from https://www.bls.gov/regions/new-england/news-release/occupationalemploymentandwages_boston.htm

US Department of Labor and Statistics. (2020). Stats-Austin. Retrieved from https://www.bls.gov/oes/current/oes_tx.htm

US Depatment of Energy. (2017). Water and Wastewater Annual Price Escalation Rates for Selected Cities across the United States . US Depatment of Energy.

US Energy Information Administration . (2020). Regional Energy Rates for Different Practices. Retrieved from https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a

USDA. (2020). USDA-Reports. Retrieved from https://usda-reports.penguinlabs.net/?crop=rent_cash_pastureland&statistic=expense_dollars_acre&year=2019

USDA- NASS. (2020). USDA- NASS. Retrieved from https://www.nass.usda.gov/

WHITCHER, J. L. (2019). US Patent No. 10,306,847.

Wholefoods Market. (2020). Retrieved from https://products.wholefoodsmarket.com/

worldatlas. (2018, May 10). Retrieved from https://www.worldatlas.com/articles/what-is-the-environmental-impact-of-agriculture.html

Xiaodong Du, H. F. (2016). Rationality Of Choices In Subsidized Crop Insurance Markets. Agricultural And Applied Economics.