Economics of Vertical Farming: Quantitative Decision Model and a Case Study for Different Markets in the USA

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Abstract

There are various problems associated with our conventional practice of farming. Agriculture is responsible for mass 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 for practices of conventional farming. 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 mentioned issues associated with traditional farming by using considerably less water, requiring less land, and not relying on the environmental conditions whatsoever. However, vertical farming is also energy and labor intensive and can be quite expensive in some cases. This study works to quantitatively model and evaluate the economic prospect of vertical farming as a business venture in a competitive marketplace under different circumstances. A generalized quantitative framework to evaluate vertical farming with respect to traditional farming is developed. Then, the developed framework is employed for a case study to evaluate the merits of vertical farming in several locations around the US by measuring the relative profit and risk. The results quantify the value proposition of the practice in various conditions and help evaluate the current and future prospect the vertical farming industry.

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1 Introduction

Agriculture and activities associated with it have been known to have a variety of harmful environmental impacts (worldatlas, 2018). 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 mass deforestation (Milius, 2017). Some of the other environmental impacts associated with agriculture are soil degradation, over irrigation, and pollution; each contributing to environmental hazard in some way. In the past 25 years alone, agriculture has been responsible for wiping out around 1 million square kilometers of forests (Environment, 2020) (Geography, 2019). Moreover, Irrigation currently uses up to 80% of our freshwater, globally (USDA, 2018). 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. The population growth, creation of new industries, and economic expansions are expected to intensify this major concern in the coming year. So, we have a global water problem that might not go away any time soon, and agriculture is the main consumer.

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 increasing world population and food per capita consumption, it is getting more difficult to sustain this form of practice. Moreover, conventional farming is heavily reliant on the environment, but due to global climate change, rainfall and pesticide patterns are changing, and weather extremes are becoming more frequent. Hence, our conventional farming practices can be risky. This is empirically observable in the farming insurance payout increases over the past years. Overall, we can see that exploring new methods of sustainable agriculture, while reducing the environmental impact, and minimizing its water usage can be of great importance to our future food, water, and environmental safety.

There have been a variety of new technologies looking to reduce the mentioned harmful effects of agriculture. Different types of vertical farming are of these new methods. Vertical farming is a practice 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 produced by vertical farming systems are lettuce, tomato, basil, cucumber, flowers. Vertical farming businesses are typically set in either shipping container environments (Freight Farms, 2020) or large-scale warehouses (Aerofarms, 2020).¹ A more detailed review of main vertical farming technologies is provided in Appendix Section.

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 also means that there would be no deforestation and desertification effects spawn by this method of farming. Moreover, vertical farming's production efficiency are independent of its surrounding climate. Therefore, global warming and climate volatility, in general, would have no impact on its performance. That could also lead to more reliable production predictions and reduced risk. Another advantage of vertical farming is its frugal water consumption. For instance, hydroponics farming, the most common method of vertical farming, generally consumes 90% less water to deliver crops compared to traditional agriculture (nps, 2018). Fewer pests and diseases, better growth rate, and efficient use of nutrients are

¹ In this study, we examine Vertical Farming in hydroponics or aeroponics settings as they are known to be more commercially viable practices. 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 in this study.

other advantages of vertical farming. However, vertical farming has its own range of problems as well.

Vertical Farming can also be quite expensive as it is energy and labor intensive. Also, most vertical farming ventures in today's world are pretty small in scale compared to other types of farming. For it to succeed in the marketplace, it must compete with a large scale, highly optimized traditional agriculture. That puts vertical farming's financial prospects in a questionable state at best. Vertical farming has a lot of promise from a macro perspective with regards to the issues we reviewed. But these advantages can often seem irrelevant from a business economics point of view. After all, even in a more tolerable flashy fundraising/market share culture of today's investments, a business is still expected to eventually make a profit in the competitive marketplace.

Vertical farming is a relatively new industry, and it might play a role in helping establish the future of our food sustainability and helping the environment. However, there has been limited scholarly research on vertical farming. Among those few most focus on the technology and agricultural aspect of vertical farming. Only a limited number of researchers have chosen 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. Moreover, a quantitative economic evaluation measures must exist to inform policy makers, industry stakeholders and researchers. Thus, there is a need for more fresh perspectives to analyze vertical farming from an economic and business point of view. This study aims to quantitatively model vertical farming's performance and economic prospect with respect to traditional agriculture under different circumstances in a competitive market. We propose a framework to evaluate both the profit and risk prospects of vertical farming with respect to conventional farming. This framework can be utilized to evaluate various farming businesses in different markets. We utilize the proposed framework to conduct a case study regarding the prospect of vertical farming in a series of locations across the United States (US). Our results identify the best and worst markets for implementing Vertical Farming. We also analyze and report the most influential factors on Vertical Farming viability. We leverage these results to develop an evidence based discussion regarding the Vertical Farming industry and business practice from a macro perspective. We identify the major challenges the industry faces on a macro level, discuss the future trends that might change industry and how that future could look like.

To the best of our knowledge, there have been no prior literature attempts to develop models and frameworks that evaluate vertical farming with respect to conventional agriculture under different conditions and locations in a competitive marketplace. 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. Our work can inform policy makers and industry stakeholders in this field. Moreover, the proposed methodology here can be used by future researchers to evaluate various farming practices.

2 Literature Review

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.

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. (Cicekli & 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. In a more recent work, (Moghimi, 2021) takes more macro approach and discusses the underlying tradeoffs of a vertical farming practice and their relationship with respect to future economic trends.

Only a few scholarly projects in this field look to analyze vertical farming quantitatively and evaluate its 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. There are important factors usually missing in the mentioned case studies. It is often ignored 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 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 do not take into account the risk aversion aspect of vertical farming altogether. In addition, most of the literature in the field assesses vertical farming in a micro scale.

(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 (2) that can be applied to a variety of cases. (3) Moreover, this study conducts 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 and empirically tested model. (5) 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

3 The Quantitative Framework

3.1 Defining the Problem

In any farming practice, vertical and conventional included, a system consumes a series of resources to produce goods in the form of crops. This production of course comes with a range of potential risks for each practice. In this segment, we seek to quantitatively model the relative profit margin and the relative risks of implementing a

vertical farming business with respect to traditional farming in various locations. Then we go on to build on a decision model to evaluate the relative appeal of vertical farming from an economic standpoint for different types of stakeholders, in different regions. It is important to address the main tradeoff procedure that was considered in the making of this framework. On the one hand, we want our model to be as accurate as possible. Meaning ideally, it would include all the relative parameters, variables and the complex relations among them. On the other hand, however, Vertical Farming is a young industry where none of the companies are publicly traded. We have also mentioned that economic empirical research concerning this practice is also very limited. In other words, constructing the most comprehensive and complex theoretical framework for evaluating vertical farming might be a moot point at this stage as the required data to utilize and validate that complex framework may not be available. Hence, our efforts here are dedicated towards building good theoretical evaluation framework that would be compatible with the limited data availability in this field. So, that we could test, validate, and utilize the framework in a real world setting to generate information that is of value.

3.2 Parameters and Relation

3.2.1 The Main States

The first step in formulating this framework is to define the states in which the parameters are defined in. In this segment we discuss the main influencing state variables and address the simplifying assumption to make the framework more general and applicable. It should be noted that a detailed stochastic framework has been proposed in recent literature (Moghimi F. B., 2020). However, given the scarcity of data concerning this topic, we view our simplifying assumptions as necessary for conducting practical experiments and extracting useful insights grounded in reality.

Location (i): 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 regional area and its surroundings. We take into account the impact of location in our framework.

Concept of time: Introducing a time series setting state to our analyses could indeed improve the accuracy of our estimations, theoretically speaking. It could also potentially help us develop a stochastic framework for evaluation. After all the energy rates in Austin in the winter of 2020 indeed differ from energy during the summer of 2015 in the same location. This difference can indeed influence the financial prospect of a farming business. However, we simply don't have access to that time series data for every variable influencing farming perspective (labor, energy, water, etc.) for each location. It can be argued that it generated complexities and missing data may not be worth the trouble. So, we relax the concept of time in this study by assuming that any established farming would continue its work for a year in a single location. All of the parameters in question from this point forward will be estimated assuming a full year of production for both the field grown and vertical farming operations.

Scale variable: In every investment and business venture, the scale matters, and this case is no different in farming. Here we address the issue of scale 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 2) or factory farms (Figure 1). 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 since their goal is to sell/lease out 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 1. Aerofarms (Aerofarms, 2020) vertical farming which is the most prominent factory farm using vertical farming²

² This picture was taken from the Aerofarm company website (<https://aerofarms.com/>)

Figure 2. Evergreen lab's (Evergreen- Txstate, 2020) container vertical farming operation

Product state variable: The last state condition takes into account the product type. Of course, the product a farming system produces influences its performance, economics, and risks. 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. For the purpose this study, this variable is relaxed by assuming that the vertical farming venture in the discussion will only produce 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. Our final reason for choosing lettuce as the benchmark for our model is simply the availability of more reliable data. The data concerning vertical farming is considerably limited overall and of that limited data, the majority does indeed belong to lettuce and other leafy green productions.

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

Very limited data on the sales information of vertical farming is available. So, chose to provide an applicable indicator for measuring the profit potential of a farming practice in this segment. So, we argue that an overall profit margin estimation based on sales price and production costs per capita would give us an applicable model to utilize. 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:

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

Equation 1. Cost of production relations

Since this study works to evaluate vertical farming in various locations on a relative basis, the initial machinery investment would not influence the decision as it is more or less the same in any location in our case study³. 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

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:

$$\text{Farming Risk} = f(\text{production risk, price or market risk, financial risk, institutional risk, human or}$$

³ In other words, including the machinery costs would not add notable information in the comparison setting as it is approximately similar in different regions. So, adding them might introduce an unrewarded level of complexity to the model.

personal risk)

Equation 2. Farming risk relations

That said, one could argue that the latter 4 types of risk, all except production risk, are mostly independent of the type of farming practice. In other words, practicing vertical or field grown farming will not generally influence the price risk or human risk one faces. This argument can be extra appealing if we are analyzing a business from micro business econ perspective. With that in mind, as we seek to evaluate vertical farming with respect to conventional farming in this study, the main differing risk factors between the two is indeed the production risk. So, we will only focus on production risk for the remainder of this study. So we shall have :

Simplified Farming Risk $\sim f(\text{production risk})$

Equation 3 Simplified farming risk relation

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 a conventional farming 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 are also available numerically in large chunks of data. Let us define:

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

Equation 4. 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	M ² /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/M ²	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
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 5
Production Cost Per kg for traditional farming (field grown) practice	USD/kg	CT	As defined in Equation 6
Profit margin of growing crops in location i with vertical farming practice	%	PV	As defined in Equation 7
Profit margin of growing crops in location i with traditional farming practice	%	PT	As defined in Equation 8
Relative profit margin appeal of growing crops in location i	%	PA	As defined in Equation 9

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:

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

Equation 5. 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:

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

Equation 6. 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 7. Profit margin for a vertical farming practice in location i

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

Equation 8 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 9, 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 9. Relative profit margin appeal of implementing vertical farming in location i

Equation 9 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 10
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:

$$RA(i) = (1 - SR(i)) \cdot IR(i)$$

Equation 10. 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 10. 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 9 and Equation 10 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:

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

Equation 11. minmax scalar function

Equation 11 normalizes the values of a data set between 0 and 1 based on the minimum and maximum values of the said set. Using the minmax scaling tool let us define Profit Decision Indicator (PDI) and Risk Decision Indication (RDI) as follows:

$$PDI(i) = \text{minmaxscalar}(PA(i))$$

Equation 12. Decision indicator based on regional costs

$$RDI(i) = \text{minmaxscalar}(RA(i))$$

Equation 13. 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 14. 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 15. 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 16. The decision model for locating the best vertical farming location

4 Case Study

In this segment, the proposed framework 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.

4.1 Performance Benchmark

First, we seek to establish a technology performance benchmark for both practices in order to utilize the proposed framework in our analyses. As mentioned before, our benchmark should reflect a common large scale (90,000 kg annually) lettuce production vertical farming operation that will continue to produce for at least a year. We seek to analyze that benchmark with respect to a conventional farming practice with similar characteristics. Our benchmarks refers to a series of parameters that would reflect the performance of each practice. This refers to parameters such labor requirement per kg of production, energy required per kg of production, water required per kg of production, yield, and land required for a kg of production. This information is acquired by reviewing the existing literature and practicing businesses for both practices (urbanagnews, 2020) (Barbosa, 2015), (Galinato, 2013), (Toyoki Kozai, 2016), (Djevic, 2009), (allardo M, 1996), (Hussain, 2009) (Helmer, 2019) (IGrow, 2015), (Technofarm innovation, 2020), (Tasgal, 2019), (cambridgehok, 2020), (SPREAD, 2020). 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” and “Vertical Farming” is generated, as seen in Table 3. It is very important to address that our case study would check for any possible errors in the estimated benchmark values by conducting a series of sensitivity analysis. The sensitivity analyses would also help us examine the validity of our findings.

Table 3. Benchmark performance values for practicing tradition and vertical farming

Parameter	Traditional Agriculture (field grown)	Vertical Farming
Production per year benchmark (kg)	907184.7	907184.74
Labor per kg (manH/kg)	0.014	0.066666667
Energy consumption per Kg (KWH/kg)	0.575	5.75
Water consumption per kg (L/ Kg)	250	20
Yield (Kg/M ² /Year)	4	150.2334586
Land ratio for 1 kg production in a year(M ² /kg)	0.25	0.006656307

4.2 Locations

Let us first clarify the borders of the analyses 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 4. The locations are selected in a manner to provide a broad perspective on 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.

Table 4. Location list

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

4.3 Alternative Location Data

This case study seeks to evaluate vertical farming in a series of location. To do this by utilizing the framework, we

will need regional data from each alternative location. In this segment, we gather the alternative location data along with credible sources for all the seven locations. It is important to note a few 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. Third, it should be noted that the land 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. Fourth, we assume the rates are constant. Alternative analysis with different rates can be conducted similarly. Moreover, the regional insurance and subsidy rates for are 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 realized 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. With that said, the regional data collected is presented in Table 5.

Table 5. Regional rates with their references

City Name	State Initial	Median Farm Labor Cost (USD/Hour)	Industrial Energy Rate (USD/KWH)	Fertile Land Monthly Rent (USD/Acre)	Non-Fertile land rent (USD/Acre)	Insurance Subsidy %	Insurance Premium per Acre (USD/Acre)	Water Price (USD/L)	Price of lettuce(USD/Head)
Austin	TX	11.61	0.054	42.5	6	0.7	74	0.0012	1.99
Boston	MA	17.36	0.139	88.5	35	0.63	160	0.0014	1.79
Chicago	IL	16.6	0.066	224	41	0.57	43	0.0012	1.99
Des Moines	IO	14.6	0.062	230	59	0.54	32	0.001	1.99
Los Angeles	CA	16	0.12	423	13	0.59	31	0.0016	1.79
Miami	FL	12.67	0.072	110	15.5	0.63	53	0.0012	1.99
New York	NY	15.6	0.052	66	26	0.7	26	0.0014	1.49
Source	(US Department of Labor and Statistics, 2020)	(US Energy Information Administration, 2020)	(USDA, 2020)	(USDA, 2020)	(USDA, 2020)	(USDA-NASS, 2020)	(USDA-NASS, 2020)	(US Department of Energy, 2017)	(Wholefoods Market, 2020)

4.4 Experiment: Analyzing the Location Alternatives

4.4.1 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, w_1 and w_2 values are set at 80% and 20%, respectively. Figure 3 illustrates the relative economic appeal of each location alternative. Table 6 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 3. $LA(i)$ with $w1=0.8$, $w2=0.2$

Table 6. 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 framework 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 efficacy advantage over any form of vertical farming as it can be seen in the $PA(i)$ column of Table 6.

4.4.2 Sensitivity Analysis

Here, a series of sensitivity analyses are conducted to evaluate the effect of potential change or error in our performance benchmark on our results. This sensitivity analysis helps validate the generated results and checks the robustness of the decision model.

4.4.2.1 Scenario 1

In this scenario, we assume that vertical farming operations have become 25% more efficient⁴, which could be due to errors in benchmark estimations, a plausible growth of technology in the future or simply implementing a superior technology when compared to the benchmark estimates we provided earlier in Table 3. As our evaluation works on a relative basis, traditional farming benchmark will remain constant during this step. The results for scenario 1 sensitivity analysis are presented in Figure 4.

Figure 4. Scenario 1 scores

It can be seen from the results (Figure 4) that in the event of implementing a superior vertical farming technology relative to the benchmark, Austin would still be the best location alternative. Moreover, Miami and Des Moines are still the second and third best choice, respectively.

4.4.2.2 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 our initial performance benchmark (Table 3). The results for scenario 2 sensitivity analysis are presented in Figure 5.

⁴ In other words, our vertical farming operation will have the same output with 25% less energy, land, water, and labor.

Figure 5. 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 that the top three choices are still the same.

4.4.3 Overall Confidence in the Results – Validation 1

Considering the two sensitivity analysis scenarios, the confidence level of the framework's decision is decent. The initial results seem unphased during both scenarios. In other words, the framework 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 initial benchmark. This observation is good news for the framework 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, experiment such as this could help increase our confidence in the results.

4.5 Impact of Stakeholder Preferences

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

4.5.1 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 (w_1, w_2) used in the model. 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. In this scenario, the decision model assumes an equal importance weight among the risk aversion and profit margin indicators. Figure 6 illustrates the results under the 50-50 scenario.

Figure 6. $LA(i)$ for $w1=0.5$, $w2=0.5$

The results provided in Figure 6 and Table 7 take another reassuring step towards validating the decision model's initial suggestion. We can see that Austin would still be the best location alternative even if the stakeholder were more risk averse 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 7. 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%

4.5.2 Impact of Stakeholder Preferences on a Broad Scale

In this segment, the framework 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 7 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 7. framework scoring in the w1, w2 spectrum

4.6 Extreme Cases- Validation 3

In this segment, we seek to analyze two extreme location alternatives to test the boundaries of the decision model. This analysis seeks to investigate the framework'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 framework to recognize the extreme 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 **Error! Reference source not found..**

Table 8. Extreme alternative location data

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

Figure 8 shows the decision model results 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 8 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 8. Extreme alternative evaluation

4.7 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 more uncertain grounds. That said, this study validates the results in four major steps:

Production Technology Sensitivity Test (4.4.2): 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 (4.5.1) : 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 averse.

Extreme Location Alternative Test (4.6): This experiment tested the framework evaluation results in two extreme locations. The framework successfully identified and ranked extreme locations, respectively.

In Line with Existing Understanding of Vertical Farming: The results are fairly in line with the current understanding of vertical farming operations. Vertical farming is commonly known as energy and labor-intensive, risk averse, 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 Future of Vertical Farming

In this section, we seek to gain some perspective into the future of the vertical farming industry by utilizing our results from the case study.

5.1 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 9 illustrates the average values associated with different production costs of both farming practices.

Figure 9. 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. We should bear in mind that automation is a double-edged sword between competing industries; in other words, it can occur in both vertical and conventional farming. That said, there is a good argument to assume that vertical farming would be the faster industry to progress technologically as it could have a considerably higher learning rate by having access to the data gathered from its enclosed farming factory and having full control over the environment that the plants are produced in.

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.

Post-COVID World and the Desire for Local Food: A Post COVID world might have a higher demand for locally grown food, and if that happens to be the case, it could favor vertical farming's prospect, especially if more viable methods are established to grow a greater variety of crops.

5.2 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 averse 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 B. K., 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.

To sum up, our results indicate that similar to other "sustainable technologies" such as solar energy in its early days; the market is not fully ready to accept vertical farming's price implications on its own as of now. This leads us to predict that any large-scale adoption of vertical farming in the near future will most likely rely on government intervention and incentive restructuring. Perhaps policy changes concerning climate change risk and water associated subsidies. Whether that would be something desirable or not is a good question and it is better left for agricultural economists.

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 for 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. It might plausible 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). A lot of effort has been dedicated towards improving vertical farming technology. That said, considerable growth in any industry would also require ample effort and investments dedicated to forming a better understanding of the field in terms of economics. 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. Therefore, this study's material seeks to help with this need in an expanding industry.

This study provides a comprehensive set of models that can be utilized as a business/economic analytics tool to evaluate vertical farming. Moreover, the study proposes a flexible decision model for choosing the best location alternatives of vertical farming in a competitive marketplace. As the vertical farming industry grows, it will attract more interested parties to its ecosystem, investors, policymakers, analysts, scholars, etc. Our proposed framework is flexible enough to help them in some way or form. The case study conducted in this study illustrates a glimpse of the potential insights we can acquire utilizing the proposed framework.

For future work, introducing more evaluation and validation algorithms as more data becomes available can be an interesting area to examine. In addition, introducing a decision factor under the title of "environmental hazards" could complement this study, should the required data be accessible. Finally, if enough data is gathered, one can look to introduce elements of probability into the framework and convert the deterministic decision-making model into a stochastic one.

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Appendix Section

A. Forms of Vertical Farming

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 10. 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.

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

Aeroponics

Unlike hydroponics or aquaponics, aeroponic system nourish plants without a liquid medium using nothing but nutrient- charged mist (**Error! Reference source not found.**). 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 12. 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.

B. Comprehensive Worksheet

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

Table 9. 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 10. 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 11. 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 12. 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	0.38125	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	0.04128	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	0.0014 83	0.0086 49	0.0101 31	0.01457 9	0.00321 2	0.0038 3	0.0064 25	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	0.0012 08	0.0014 5	0.0012	0.001	0.0016	0.0012	0.0014 13	0.1	0.00001
Water Cost (VF) USD/kg	0.0241 67	0.029	0.024	0.02	0.032	0.024	0.0282 52	2	0.0002
Water Cost TF USD/kg	0.3020 83	0.3625	0.3	0.25	0.4	0.3	0.3531 47	25	0.0025
VF V Cost USD/kg	1.1081 02	1.9856 41	1.5119 59	1.34935 6	1.78868 8	1.2809 67	1.3695 95	2.095516	12.41687
TF V Cost USD/kg	0.4982 41	0.6909 32	0.5843 6	0.50420 1	0.71913 1	0.5254 03	0.6057 54	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	4.5227 27	4.0681 82	4.5227 27	4.52272 7	4.06818 2	4.5227 27	3.3863 64	11.36364	2.272727
PV%	0.7549 93	0.5119 09	0.6656 97	0.70165	0.56032 2	0.7167 71	0.5955 56	0.815595	-4.46342
PT%	0.8898 36	0.8301 62	0.8707 95	0.88851 8	0.82323	0.8838 31	0.8211 19	-1.20692	0.129818
PA	- 0.1348 4	- 0.3182 5	- 0.2051	- 0.18687	- 0.26291	- 0.1670 6	- 0.2255 6	2.022516	-4.59324
PDI (Scaled PA)	0.6739 06	0.6461 83	0.6632 87	0.66604 2	0.65454 8	0.6690 36	0.6601 93	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	0.0313 68	0.0630 94	0.0260 66	0.02067 9	0.01780 6	0.0276 67	0.0107 9	1	0
LA(i, w1=0.8,w2=0.2)	0.5453 98	0.5295 65	0.5358 43	0.53696 9	0.5272	0.5407 62	0.5303 12	1	0
LA(i,w1=0.5,w2=0.5)	0.3526 37	0.3546 38	0.3446 77	0.34336	0.33617 7	0.3483 52	0.3354 91	1	0

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