Market Analysis for Terrestrial Application of Advanced Bio-Regenerative Modules: Prospects for Vertical Farming

Chirantan Banerjee

MARKET ANALYSIS FOR TERRESTRIAL APPLICATION OF ADVANCED BIO-REGENERATIVE MODULES: PROSPECTS FOR VERTICAL FARMING

Masterarbeit

im Rahmen des Masterstudiengangs

Food and Resource Economics and Management

zur Erlangung des Grades:

Master of Science (MSc.)

der

Hohen Landwirtschaftlichen Fakultät

der

RHEINISCHE FRIEDERICHS-WILHELMS-UNIVERSITÄT

zu

Bonn

vorgelegt am: 17. Juli 2012
von cand.agr.Chirantan Banerjee
1. Prüfer: Professor Dr. Ernst Berg
2. Prüfer: Dr. Carola Grebitus

Contents

List of Figures

List of Tables

List of Abbreviations

Acronym:	**Full form**
AD:	Anaerobic Digestion
AOCS:	Attitude Orbit Control System
CATIA:	Computer Aided Three-Dimensional Interactive Application
CE:	Concurrent Engineering
CEF:	Concurrent Engineering Facility
CHP:	Combined Heat and Power
CSTR:	Continuous Stir Type Reactor
DLR:	Deutsches Zentrum Für Luft- und Raumfahrt, German Aerospace Center
ECB:	European Central Bank
EPA:	The U.S. Environmental Protection Agency
ESA:	European Space Agency
FAO:	Food and Agricultural Organisation
FAOSTAT:	Food and Agricultural Organisation Statistical Database
FVSW:	Fruit and Vegetable Solid Waste
G:	Giga
GU:	Germination Unit
H:	Hour
HA:	Hectare
HDVG:	High Density Vertical Growth
HRT:	Hydraulic Retention Time
IPSP:	Initiation/Preparation/Study/Post-processing
ISS:	Institute of Space Systems of The DLR
J:	Joule
K:	Kilo
K/O:	Kick-off
KTBL:	Kuratorium für Technik und Bauwesen in der Landwirtschaft
LED:	Light Emitting Diode
M:	Mega
NASA:	National Aeronautics and Space Administration

Acronym:	**Full form**
NDS:	Nutrient Delivery System
OLR:	Organic Loading Rate
PI:	Prime Investigator
PPF:	Photosynthetic Photon Flux
S/S:	System and Subsystem
STK:	Satellite Tool Kit
SWOT:	Strengths Weaknesses Opportunities Threats
TH:	Thermal
TS:	Total Solid
U.N.:	United Nations
USDA:	United States Department of Agriculture
VF:	Vertical Farm
VS:	Volatile Solid
W:	Watt

Acknowledgment

I would like to extend my sincere acknowledgement to the German Aerospace Center for initiating this research project. The organisation has invested with time and resource including a three day Concurrent Engineering Study, which made this body of work possible. Instrumental in this endeavour was Mr. Daniel Schubert and his colleagues who supported with their insights and expertise. Mr. Schubert also served as the tutor of this project, reviewing it time and again and making key suggestions which gave the work its present structure and meaning.

I would also like to extend my thanks to all the colleagues of the Advanced Study Group for their cooperation and camaraderie. A concerted effort was the key to the detailed analysis that was achieved despite the theoretical nature of this work. Special thanks goes to Mr. Vincent Vrakking for his illustrations, which really speak a thousand words.

My sincerest of thanks goes to Mr. Conrad Zeidler. He was not only a tutor but a patient teacher and great colleague to work with. The numerous queries he answered, the amount of effort he put into this work and the faith he had in me, went a long way.

It is a futuristic work, usually met with insurmountable scepticism which is justifiable in its own rite. Despite that, the people and organisations who lay their faith in science and its power to bring paradigm shifts are the ones who must be congratulated.

Above all I would like to thank Ms. Ulrike Ziegler for her patient editorial efforts and attention to details, without which this work would not have been in the desired form.

Part I

Paradise Lost

In order to support human ambitions of deep space colonisation, national and international space agencies have been investigating possibilities of deployment of habitats on Moon and even Mars. An integral part of this programme is the bio-regenerative life support system. This aims to decrease the supply mass by regenerating essential resources for humans. The Institute of Space Systems of the German Aerospace Center (DLR-ISS) at Bremen, is responsible for investigating and developing space applications. However, terrestrial applications of the technology is also on their agenda. One such application lies in growing crops in vertical farms in the heart of cities, which is said to be a greener way to produce food. The idea is still unproven although there are abundance of architectural plans and artists impressions to be found on the web. When it comes to scientific papers, or economic analysis of feasibility, scalability and practicality of this concept, there is no such work to be found[1]. While on one hand this is a handicap on the other hand, it opens the opportunity to do a seminal work.

The greenhouse technology has advanced over a century. It is now possible to control temperature, humidity, lighting, airflow and nutrient conditions for optimal productivity of plants, irrespective of season and agro-ecosystems. Hydroponics has equally developed to enable cultivation of wide variety of crops without soil. Thereby freeing future agriculture of yet another constraint namely land. It essentially involves suspending plants in a medium—such as gravel, wool or a form of volcanic glass known as perlite while the roots are immersed in a solution of nutrient-rich water. A constant flow of air often enriched with carbon dioxide ensures optimal conditions for plant growth. Any nutrients or water not absorbed by the roots can be recycled, rather than letting it run-off thus preventing ground water pollution. Aeroponic methods developed at NASA furthers this by spraying nutrient rich mist at the root zones.

The idea behind vertical farming is that of skyscrapers with floors stacked with orchards and hydroponic/aeroponic beds, producing crops all year round. Along with challenging the hitherto inconceivable concept of creating more arable land, this would slash the transport

---

[1] As of 10th July 2012

costs and carbon dioxide emissions associated with moving food over long distances. It would also reduce post harvest spoilage of food and free agriculture from the grips of unpredictable weather and pest and disease attacks. The use of pesticides, herbicides and fungicides can be kept to a bare minimum through cultivation in a controlled environment. Production can be accelerated through controlled environment agriculture by optimising photo-duration and providing critical wavelengths, which may also lead to significant rise in yield and year round production. Soil erosion will not be a problem because the food will be grown hydroponically/aeroponically. Through recycling, only a fraction of the amount of water and nutrients will be needed compared to conventional farming. Additionally it holds the promise of micro climate improvement and positive psychological effect on inhabitants of mega-cities.

Chapter 1

World Statistics

According to the United Nations World Food Programme, nearly 1 billion people go hungry around the globe, in December 2008, it was an estimated 963 million people around the world. About 42% of these chronically hungry people live in India and China, two of the world's most populous nations [32] (Figure: 1.2.1 gives an overview of the world population density). Because of malnutrition, one in four children in developing nations is underweight for his or her age [67]. This already unacceptable situation will worsen with growing population and therefore require new approaches towards food production to avert aggravation of this situation in the coming decades. High food prices further worsen the global food crisis. In 2008 the global food crisis, saw questions raised on food production techniques. According to the International Monetary Fund, the world market prices for food commodities rose more than 75% from early 2006 to July 2008 [73]. Consequently, increase in grain prices caused meat, egg and dairy costs to rise [66]. The effect was worst in poor nations where even modest increases in food prices can mean the difference between sustenance and starvation [57].

1.1 Consumer needs and preferences

An important concern is regarding consumer preferences. Consumers want high-quality, affordable food. Affordability matters less to some consumers, particularly those in affluent countries where food costs account for only 10% of the average income, consumers there also want choice [42]. This includes consumer preference for foods that are produced organically. Organic foods remain a high-cost luxury that three-quarters of the world's population cannot afford, particularly those in developing nations where food costs consume 50% of the average income [42]. However, consumers who desire organic foods should have that choice. Likewise, consumers who prefer abundance of efficiently produced, high-quality and affordable food should be provided as well.

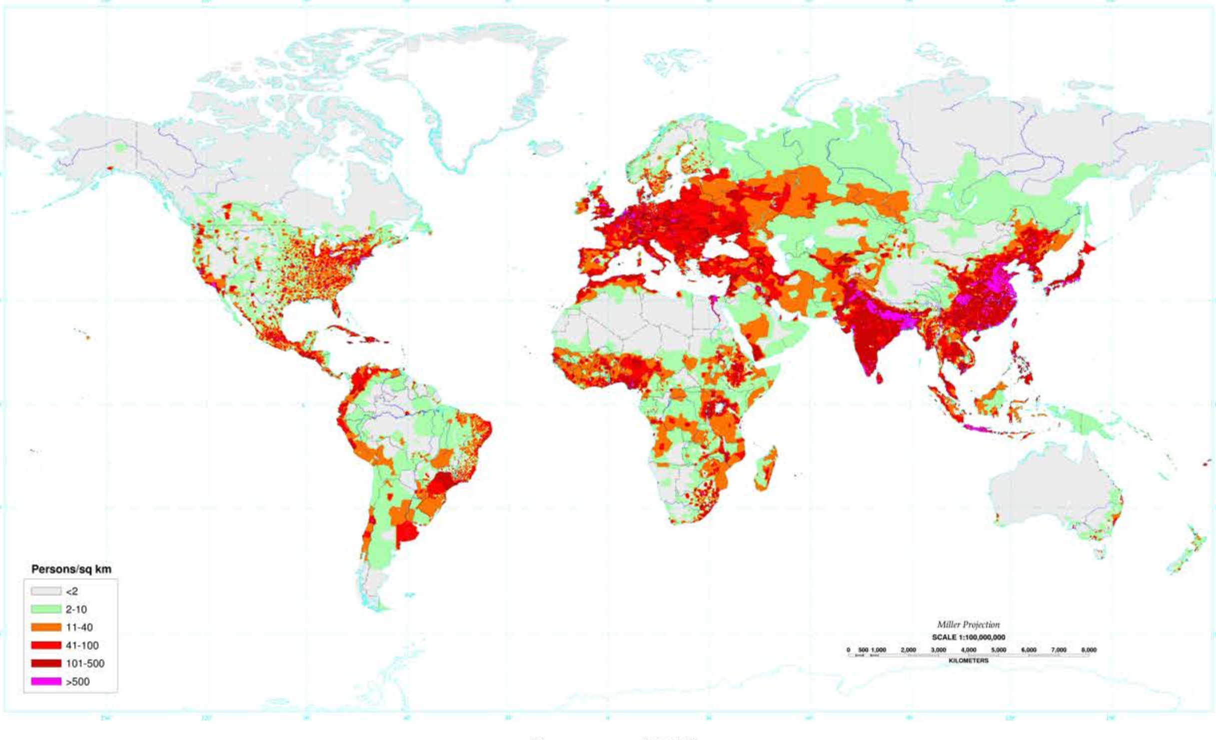
By 2050, our growing global population will require an estimated 100% more food than we produce today [72, 36]. Industrialized and developing nations alike require a sustainable supply of safe, nutritious and affordable grains, legumes, tubers, vegetables, fruits and animal protein to satisfy a rapidly growing population. Transition economies must further cater to the fast changing dietary pattern towards high protein, vitamin and mineral rich diets demanded by a population with gradually increasing purchasing power. In 1985, meat consumption in China was roughly 20 kg per person per year. By 2000, this had increased to 40 kg per person annually, a figure that's projected to more than double again by 2030 [39]. Consequently, the U.N. FAO projects that global production of meat and dairy protein will almost double by 2050 [70].

1.2 Land and desertification

Arable land is finite, with agricultural land covering 38% and arable land covering 11% of the total land area (FAOSTAT), we are operating at limits. Worldwide increases in demand for animal protein is increasingly putting pressure on natural resources, especially by increasing demand for land resources [33]. Based on FAO projections, 13% more land in developing countries will be converted to agricultural use in the next 30 years [31]. From a global perspective this amounts to a meagre 2% increase from the 38% of global land area used in 2008 to a total of 40%. This land expansion will account for only 20% of future increases in food production. Another 10% additional production can be projected from increased cropping intensity [31]. Therefore for the rest 70%, we will have to call upon innovation of efficient technologies and also judiciously use the ones at hand [66].

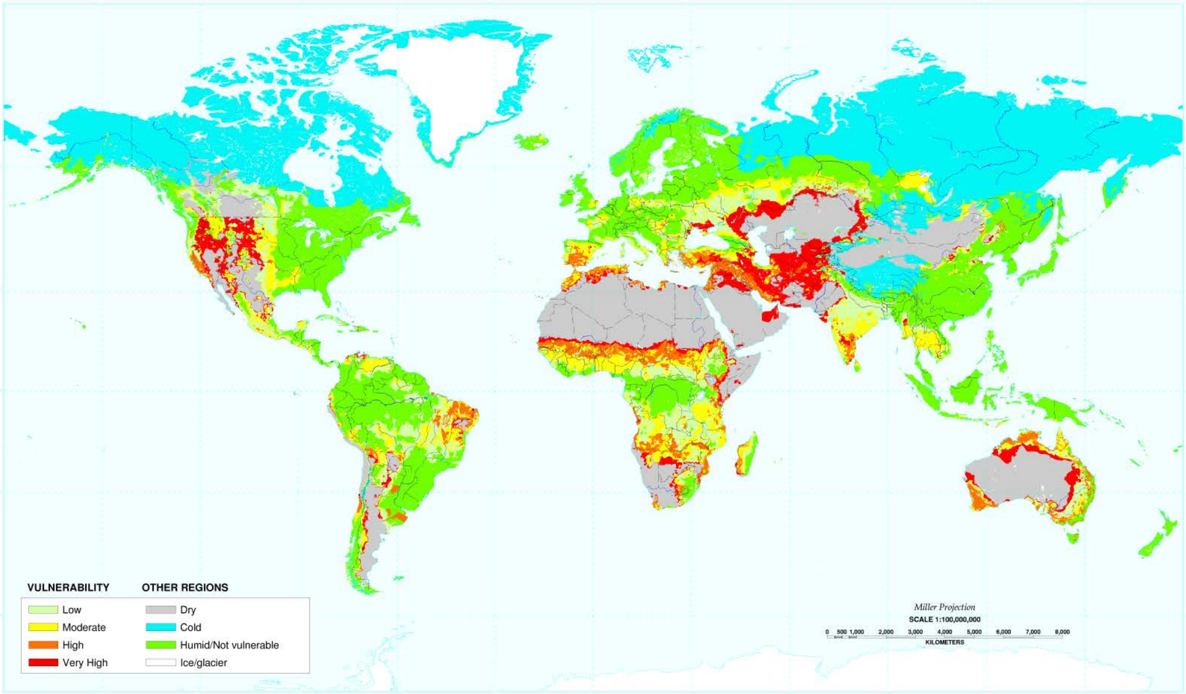
In addition to the fact that land is limited and reclamation is a slow process often coupled with environmental degradation, we are also losing land at an alarming rate due to climate change and desertification (see Figure: 1.2.2). So there is an increased need for technology that can reclaim desertified land for the purpose of agriculture. While water is a scarce resource, solar energy and space is in abundance in deserts. Vertical farming technology with its inherent water efficiency, is a good candidate for agriculture in deserts.

Figure 1.2.1: World Population Density



Source: [79]

Figure 1.2.2: Map of desertification vulnerability

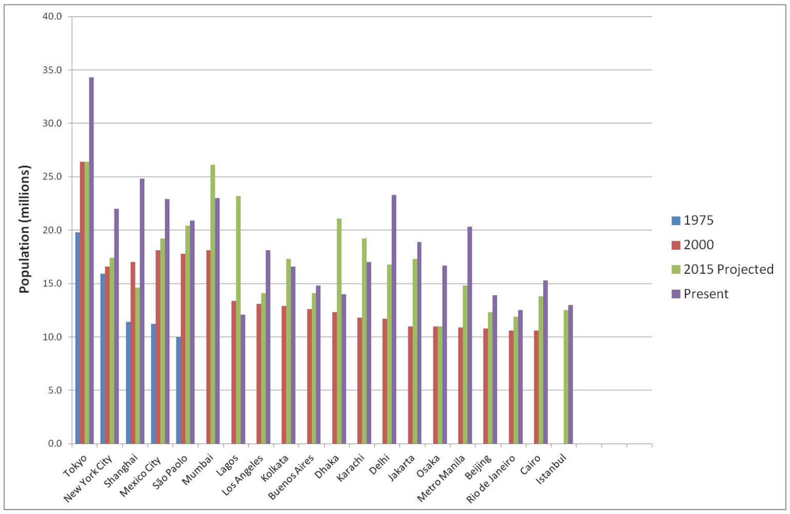


Source: [80]

1.3 Mega-cities

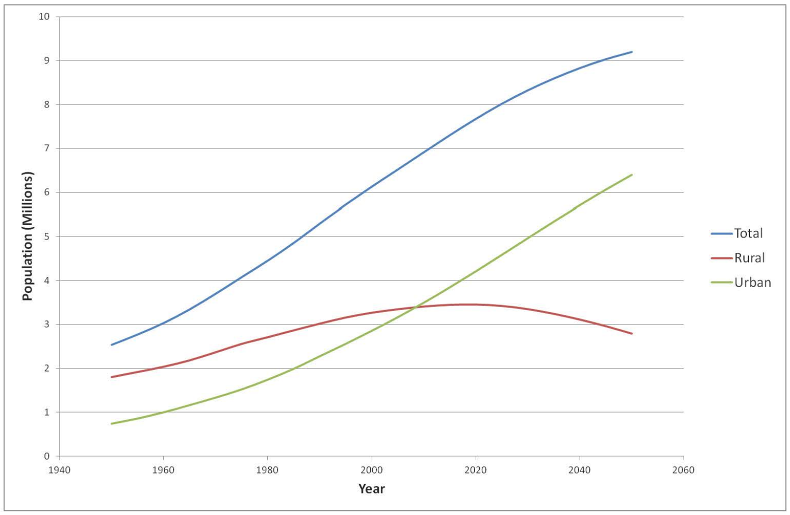
The United Nations classify a city as mega-city if it has at least 10 million inhabitants. The merger of core cities, suburbs and satellite towns have created huge metropolitan areas, and thus in recent times large agglomerates in the world with more than 10 million inhabitants have grown into mega-cities. As of 2011 there are 21 mega-cities worldwide (refer to Figure 1.3.1). For example, the area comprising Tokyo and Yokohama, inhabited by between 33-35 million people, is the world's largest mega-city. By land area, New York metropolitan region, with a total area of 8,700 sq-km is the biggest of the lot. Mumbai/Bombay, which has got a population density of almost 30,000 people per sq-km, is the world's most crowded city. Until 2025, the number of people living in urban areas will probably rise to more than 5 billion people, 90% of that increase will occur in developing countries. The explosion and growth of mega-cities worldwide may prove unsustainable, unprecedented and ecologically disastrous for human civilization. By 2000, the world's mega-cities took up just 2% of the Earth's land surface, but they already accounted for roughly 75% of the industrial wood use, 60% of human water use, and nearly 80% of all human produced carbon emissions [78].

Figure 1.3.1: Mega-cities and their population



Source: [76]

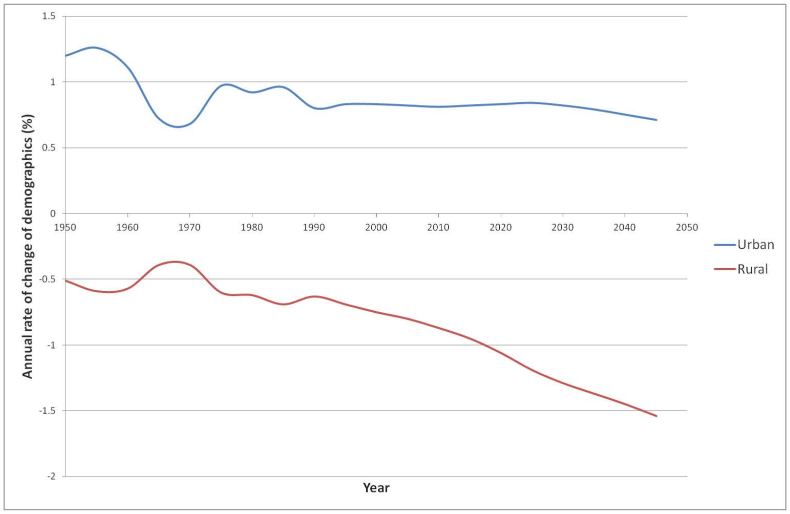
Figure 1.3.2: Total, urban and rural population growth



Source: [75]

This is however not the end as seen in the following set of figures. Figure 1.3.2 shows the relative growth of population in urban and rural agglomerates as against the growth of world population. In order to give a perspective, figures: 1.3.3 and 1.3.4 lends a sneak peek at the differential rate at which urban population is growing and the rate at which people are getting urbanised across the world respectively.

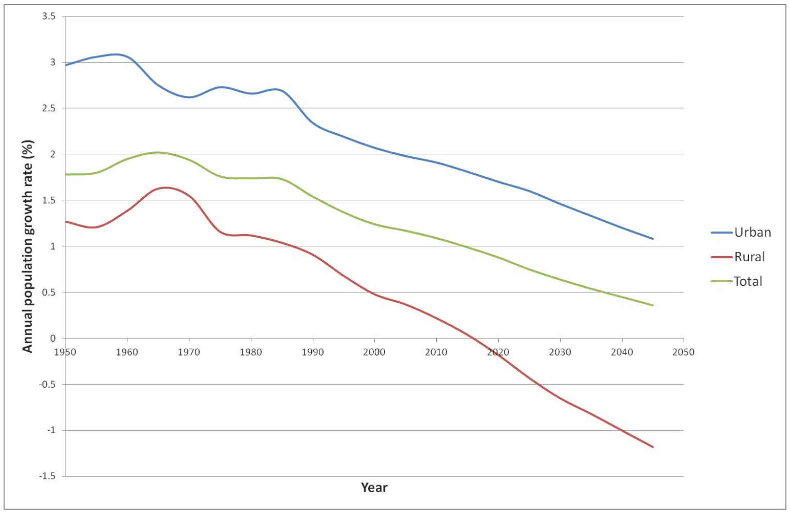
Figure 1.3.3: Annual rate of urbanisation



Source: [75]

It is clear from the above figures that the human population is not only growing but also concentrating in social agglomerates. This has mixed effect on the environment. From a macro perspective, it means concentration of service industry and less distance to be covered to deliver goods and services to the doorsteps, thus cutting on emissions. From a micro perspective, the environment of the cities are suffering a blow, with heightened air, water, light and sound pollution. Vertical farms can play an important role in solving these problems. Specialised farms have also been conceptualised for grey water purification and also to fulfil specialised task of positive psychological effect and function as lungs for the city and its inhabitants.

Figure 1.3.4: Growth rate of urban and rural population



Source: [75]

1.4 The silver lining

Agricultural science heralded phenomenal increase of productivity in industrialised nations in the last century. For instance, the average yield of corn in the U.S. rose from 39 to 153 bushels per acre [41]. A comparison of U.S. farm output for the period 1948 -2008 shows increases for all livestock and grain products. Including an 88% increase in meat production and a 411% increase in the output of eggs and poultry. This translates to a 158% increase in total factor productivity for the U.S. agriculture industry. Aggregate input use increased a mere 0.06% annually, so the positive growth in farm sector output was very substantially due to productivity growth [6]. According to the USDA Economic Research Service, the development of new agricultural technologies including advances in genetics, nutrition, disease and pest control and livestock management was an important factor in these 20th-century productivity improvements [41, 6].

Land resource is finite, the dilemma of allocation of this resource further complicates this problem. First is the environmental dilemma and the need to minimise the negative environmental effects of agriculture particularly with regard to greenhouse gas emissions, soil degradation and the protection of already dwindling water supplies and biodiversity. Therefore we need to employ such agricultural technologies that have a neutral or positive impact on our environment. The second is the economic dilemma arising from conflicting goals to allocate crop-land from growing food to producing grains for bio-fuels. The problems of protecting the environment and balancing the world's need for energy and food require a complex and multifaceted approach. Vertical farming holds the promise of addressing these issues by enabling more food to be produced with less resource use. However, its economic as well as environmental feasibility requires rigorous scientific investigation.

Chapter 2

The Vertical Farm

2.1 Definition

Vertical farming can be defined generically as a system of commercial farming whereby plants, animals, fungi and other life forms are cultivated for food, fuel, fibre or other products or services by artificially stacking them vertically above each other.

The concept of a Vertical Farm (VF) has existed theoretically since the early 1950s, there are basically three classifications debated by contemporary scholars.

1. The phrase "vertical farming" was coined by Gilbert Ellis Bailey in his book "Vertical Farming" in 1915. Bailey basically discusses an utopian concept of using explosives and other destructive technologies for the constructive purpose of agriculture and food production. He introduces the concept of underground vertical farming, something that is being put to practice presently in the Netherlands [12].

2. The second category of vertical farming falls under the concept plant life being cultivated in open air, or in mixed-use skyscrapers for climate control and consumption. This version of vertical farming is based upon personal or community use rather than the wholesale production and distribution plant and animal, in large scale. It thus requires less of an initial investment than a closed unit. Present application of this concept may

be found in Bosco Verticale in Milan.

3. An aberrant from the above concept is peripheral vertical farming, whereby crops are cultivated along the periphery of skyscrapers in moving trays, so as to uniformly provide them with ambient light. Such an example can be seen in the Paignton zoo in the UK.

4. The third category of vertical farming conceptualised cultivation of plant and animal life within skyscrapers or closed systems for the purpose of large scale production. Such systems are under trial and experimentation in numerous locations around the world and borrows heavily from the international space programmes for closed system food production technology.

While the concept of stacked agricultural production is not new, scholars claim that a commercial high-rise farm such as "The Vertical Farm" has never been built, yet extensive photographic documentation and several historical books on the subject suggest that research on the subject was not diligently pursued.

2.2 State of the art

Vertical farming is steadily becoming a subject discussed broadly in political and scientific communities. VF is a proposed agricultural technique involving large-scale agriculture in urban highrises or "farmscrapers". Using cutting-edge greenhouse methods and technologies, like High Density Vertical Growth (HDVG), these buildings would be able to produce fruits, vegetables and other consumables (e.g. herbs, pharmaceutical plants) throughout the year. The concept foresees the growing and harvesting of a wide range of plants in high density urban areas (mega cities) and the sale of these crops directly within the city community, reducing the required transportation efforts as opposed to the standard rural farming model. The advantages for this method are the multiplication of agriculturally productive land (growing in vertically mounted floors), the increase in crop yields (by using optimised production methods, such as light exposure variations, or additional CO_2 supply), the protection of the crops from weather-related problems (as opposed to outdoor farming), and the minimization of water requirements (through water recycling). The German Aerospace Center greenhouse initiative, which targets the investigation and design of a greenhouse plant production facility, would be able to contribute significantly to this upcoming field of technology.

Commercial urban greenhouses are not uncommon. Numerous crops like strawberries, tomatoes, cucumbers, peppers, herbs and spices are grown in these greenhouses filling the racks of local supermarkets. However, these are miniature in comparison to the outdoor factory farms in size, production, and economy of scale. The only silver lining is the fact that they can grow crops away from their natural agro-ecological systems all year round, cutting down transport costs, reducing the carbon footprint and in some cases serving a niche market with "home grown" food. Japan, Scandinavia, US, UK, most west European countries, and Canada have been thriving markets for these greenhouse systems. Growing freshwater fishes like tilapia, trout, as well as crustaceans and molluscs like shrimps, crayfish and mussels have also been commercialised in indoor farms.

Vertical farming is a step ahead in the sense that it envisages drastic scaling up of present indoor farming practices in vertical arrays to feed not only a niche but entire urban markets, which it claims to achieve without calling upon any resource beyond city limits. An estimated 28$m^2$of intensively farmed indoor space is enough to produce food to support a single individual in an extra terrestrial environment like a space station or space colony supplying him with about 3000 kcal of energy per day [47]. Going by that math, a vertical farm of 9300m^2(roughly the size of a city block) with 30 stories should provide around 15,000 people with 2000 kcal of nutrition per day.

2.2.1 Enabling technologies

In order to discuss the state of the art one should also discuss the technologies which are not vertical farms per say but contribute towards the technology in one way or the other.

Thanet Earth [71]: Thanet Earth, a 90-hectare greenhouse facility in Kent is the largest site in Britain [71]. Crops like tomatoes, peppers, cucumbers (not leafy greens) are all grown hydroponically using computer controlled drip irrigation. It provides 15% of the salad crops consumed in Britain and uses its own mini power-station to provide its plants with light for 15 hours a day during the winter months. Although it undermines the claim that vertical farming will save energy and cut carbon emissions, it definitely cuts on carbon footprints of crops that are otherwise imported over great distances. Using this captive power plant they can produce tomatoes round the year as against 9 month production capability of a conventional greenhouse. The bi-products namely, heat and CO_2 are re-channelled in the greenhouse system and excess power is re-fed into the national grid.

Figure 2.2.1: Thanet Earth

Source: [71]

The Science Barge [51]: New York Sun Works, a non-profit group, argue that given the present state of technology using renewable energy the numbers do not add up [15]. The Science Barge, a 120m^2 floating hydroponic greenhouse anchored in Manhattan was operated as an experimental station between 2007 and 2009 to investigate what could be grown within city periphery with minimal resource-consumption and maximum resource-efficiency. The barge used one-tenth of water required comparable field farm. There was no agricultural run-off, biological pest control was employed. Operating all year round, the yield of the barge could be 20 times more than crops grown in a field of the same size. Solar and wind energy harvesting on the barge enabled it to produce food with minimal net carbon emissions. But the greenhouses on the barge were only one story high, artificial lighting was hardly required. But stacking greenhouses on top of each other is a completely different ballgame. At the present level of technology, assuming market average of 12-18% sunlight-to-electricity conversion efficiency, generating enough electricity using solar panels requires an area about 20 times larger than the area being illuminated. For a skyscraper-sized hydroponic farm, that is presently impractical, Vertical farming might however work if it makes use of natural light.

Figure 2.2.2: Hydroponics in Manhattan

Source: [51]

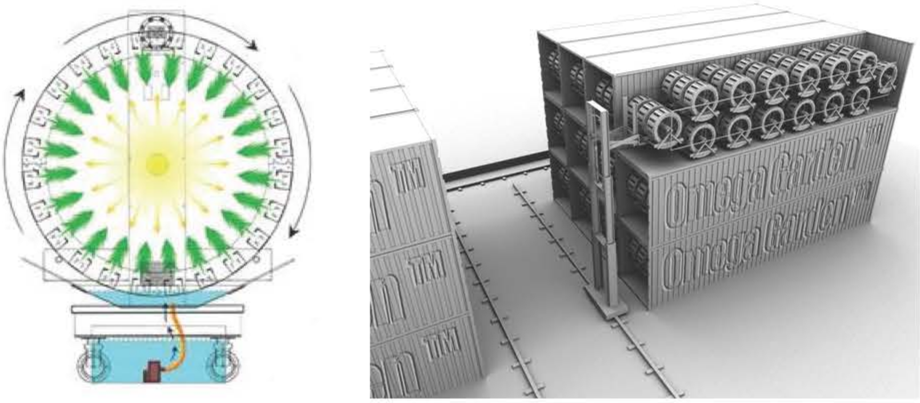
Polar Food Growth Chambers: The South Pole Food Growth Chamber, a semi-automated hydroponic facility in Antarctica is used to provide each of the 65 staff of the Amundsen-Scott South Pole Station with at least one fresh salad a day during the winter months, when supply flights to the station are extremely limited. The chamber has a floor area of 22 square meters and produces a wide range of fruit and vegetables with the help of controlled hydroponics. It does, however, require artificial lighting during winter months due to lack of natural light. DLR is presently involved in developing a similar system for the polar missions of Alfred Wegener Institute, Germany.

Figure 2.2.3: The South Pole Food Growth Chamber

Source: [18]

Omega Garden [55]: The Farmdominium or the Vertical Farming system of Omega Gardens comprises of carousels which is made up of 36 Volksgarden modules. Each Volksgarden module has approximately 20 foot square surface growing area. Rotary motion effect on plants shows an increase in growth rates of up to a factor of five observed. Horizontal carousel frame conforms to inter-modal shipping container specifications for easy shipping, and stacking. The Farmdominium is designed to be a fully automated system. Each rotating garden is a module that can be removed from the carousel if required. In turn each containerized carousel is a movable module in the larger system. This startup is based in British Columbia, Canada.

Figure 2.2.4: The Volksgarden and Farmdominium



Source: [55]

Urban Rooftop Farming [13]: BrightFarms designs, finances, builds and operates single storied hydroponic greenhouse farms at supermarkets, eliminating time, distance and cost from the food supply chain. The supermarket agrees to buy the produce and owns the farm, while BrightFarms builds it and runs it [13]. Some of their projects include, McCaffrey's Markets, Gotham Greens, Cypress Hills Community School, Manhattan School For Children, and Whole Foods Market. The present trend is in the direction of utilising the space available on urban rooftops and to pursue urban farming rather than vertical farming. BrightFarms Systems, is working with Gotham Greens, to create the world's first commercial urban hydroponic farm in Brooklyn. The 15,000 square-foot rooftop facility produces 30 tonnes of vegetables a year which is sold in local stores under the Gotham Greens brand name [35]. Such concepts will take off only when sizeable number of consumers opt for locally grown produce over imported or inorganically grown food even at a premium. However, it is clear that rooftop farming is definitely a first step before technology catches up to enable commercialisation of vertical farms.

Figure 2.2.5: BrightFarms

Source: [13]

Urban Vertical Forests [4]: Bosco Verticale (Vertical Forest) is a space saving approach for metropolitan reforestation that contributes to the regeneration of the environment and urban biodiversity without having to dedicate prime real estate in the middle of a metropolis for the purpose of ecoservices. It is a model for implementation of policies for reforestation of large urban and metropolitan areas under the name Metrosbosco. Metrobosco and Bosco Verticale are the future of environmental approach of many contemporary European cities without any trade-off between real estate and the ecology. The first example of a Bosco Verticale composed of two residential towers of 110 and 76 meters height, with a built area of 40,000 m^2, will be realized in the centre of Milan, on the edge of the Isola neighbourhood. This will host 900 trees, each measuring 3, 6 or 9 m in height apart from a wide range of shrubs and floral plants at a cost of around 65 million Euros. In terms of land area, each Bosco Verticale tower equals, in amount of trees, an area equal to 10.000 m^2 of forest. The Bosco Verticale is a system that optimizes, recuperates and produces energy. It also aids in the creation of a micro climate and in filtering the dust particles characteristic of an urban environment. The diversity of the plants and their characteristics produce humidity, absorb CO_2 and dust particles, producing oxygen. Additionally they protect from radiation, thus cutting on cooling costs and also tackles acoustic pollution, thus improving the quality of living spaces and saving energy. Plant irrigation will be produced to great extent through the filtering and reuse of the grey waters produced by the building. Additionally, photovoltaic energy systems will contribute, together with the aforementioned micro climate to increase the degree of energy self sufficiency of the two towers [4].

Figure 2.2.6: Bosco Verticale, Milan

Source: [4]

2.2.2 Pilot projects

Vertical farm in Suwan, South Korea [45]: There are recent developments relating to VF being practised or researched around the world. In Suwan, South Korea, the Rural Development Agency, is investigating Vertical Farming technology [30]. The facility is three stories in height totalling an area of 450m^2. Almost 50% of the energy requirement is supplied through renewable resources like geothermal and solar arrays, which mainly goes in meeting the heating, cooling and artificial lighting requirements. Presently lettuce is being cultivated organically through careful regulation of light, humidity, carbon dioxide and temperature, optimal levels of which is the key research question being investigated. The researchers project five years of further research before this technology is ready for the free market.

Figure 2.2.7: Vertical farm in Korea

Source: [45]

PlantLab in Den Bosch, Netherlands *[59]*: In the Netherlands, fruits and vegetables grown in similar farming environment are already available in supermarkets [12]. A company named PlantLab, has cultivated fruits, vegetables, even ornamental plants in their facility three floor underground in the city of Den Bosch. The facility of PlantLab achieves three times the yield of an average greenhouse, using 90% less water than a conventional farm. In countries with limited resources, which possesses the necessary technologies like the Netherlands, where people increasingly demand organically grown, pesticide free foods, Vertical Farms seem to an explorable option.

Figure 2.2.8: PlantLab, The Netherlands

Source: [59]

VertiCrop, Canada [83]: The VerticCrop system ensures an even distribution of light and air flow, using energy equivalent to running a desktop computer for ten hours a day it can produce 500,000 lettuces a year [83]. Growing the same crop in fields would require seven times more energy and up to 20 times more land using 8% of the normal water consumption used to irrigate field crops. VertiCrop uses multiple layers of stacked trays that operate within a single-story greenhouse, where natural light enters from above, as well as from the sides. So it is not a prototype for vertical farms. Each floor rotates its crops past the windows so that all plants receive an equal amount of natural light. This idea involves the integration of vertical farms into buildings and offices, with plants growing around the edges of the building, between two glass layers and rotating on a conveyor. This solves the natural-light problem for indoor agriculture, acts as a passive form of climate control for the buildings and also has a positive psychological effect on the residents [65, 64]. But the area available remains much smaller.

Figure 2.2.9: The VertiCrop system

Source: [83]

Plantagon Stockholm, Sweden [58]: Plantagon systems uses a variant technology between a vertical farm and a moving platform like in VertiCrop. The crops are planted on the top and they slowly move down in spiral, receiving inter-cultural practices until it completes its cultivation cycle and is harvested at the lower levels of the building. This system saves energy for lighting and heating but also restricts the whole system for cultivation of a single crop.

Figure 2.2.10: Plantagon towers, Sweden

Source: [58]

SymbioCity a project of Plantagon featuring urban agriculture takes a holistic approach to sustainable development. The urban agriculture offer proposes a new way to cultivate food by building vertical greenhouses that reduce transport costs and emissions. With a ground footprint of 10,000 m^2, a vertical greenhouse represents the equivalent of 100,000 m^2 of arable land, well suited to growing vegetables, grain and other crops all year round. Own crop production is a crucial step for a city towards securing an independent and robust food supply. By producing closer to urban consumers, the vertical greenhouse reduces transport costs and emissions and makes it possible to offer fresh food on a daily basis. Also, the vertical greenhouse produces no harmful agricultural run-off. Locating the greenhouse in the city has added benefits. Every urban area produces large quantities of surplus heat, carbon dioxide and waste that can be put to good use as fertilizer or making the greenhouse's heating systems more energy efficient.

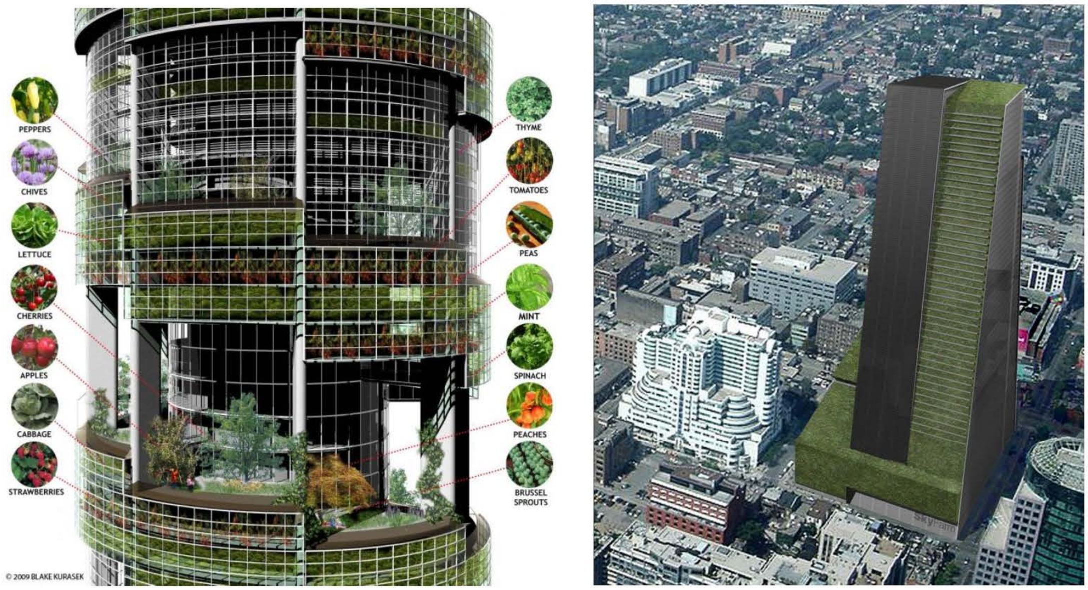
Tekniska Verken produces bio-gas from waste and will interact with a 40-meter-high greenhouse Surplus energy from Tekniska Verken heats the greenhouse Tekniska Verken delivers nutrients, CO_2 to the greenhouse furthermore organic waste from the greenhouse contributes to bio-gas production. Associated companies in this project are: Plantagon International ABB, SWECO, SAAB, Tekniska Verken and Stockholm University [58].

2.2.3 Concepts

Architectural concepts like the ones shown in Figure: 2.2.11 are plentiful on the internet. These are just two randomly chosen ones from a pool of scores of designs.

They claim the virtues of the system and the resource efficiency, without a detailed analysis of the system features, cost of production or marketability. As a result notwithstanding the innovativeness of these concepts, they fuel more scepticisms than optimism among agricultural scientists who in return argue such concepts to be utopian.

Figure 2.2.11: Vertical Farm concepts



Source: [21]

Chapter 3

Research Questions

In the later half of the last century advances in genetic engineering, plant nutrition, disease and pest control and livestock management enabled phenomenal growth in agricultural production. This helped us combat many impending famines around the world. Today we stand at a similar event horizon. Impending population explosion has brought us back to square one. By 2050 we need to double our food production. Given exponential rise of population, we must avoid a situation whereby we are called to double it again in ten years after that. We need to device methods to increase food production many times over, while conserving our resources at the same time.

In order to do a market analysis of the VF technology and assess its viability, feasibility and replicability one should ask the following questions:

1. Is vertical farming the next chapter of a long due green revolution– Does it increase food production many folds as compared to traditional agriculture?
2. Even if it multiplies the food production many times over, will it be possible to construct such a complex system from an engineering perspective?
3. What will such a farm cost– And what will a kilogram of food crop produced in such a farm cost?

4. Given the technical complexity and economic factors, where are the potential markets for such a technology? And how many of these towers can be projected to be built in the short and long term?

3.1 Methodology

To answer the above questions, inter-disciplinary research is required. The first question can be answered through the second answer. For empirical data, one has to tap on to the advances in space agriculture as well as structural engineering and industrial engineering. With the help of a concurrent engineering study conducted at the DLR-ISS, a detailed system design was worked out. This elucidated the details of equipmentation, power and structural requirement for the Agricultural, Aquacultural, Food Processing and Waste Management sub-systems with reference to the lighting, water and nutrient delivery and environmental regulation domains.

With the draft system in hand, methods of production economics and cost accountancy was applied to determine the fixed and operational cost and arrive at the cost of a kilogram of food crop produced in a VF. For the market analysis, since the plan is in a concept phase, market surveys had to be ruled out. A SWOT analysis was done through literature review and desktop research. Further, the market potential of this technology was estimated though logical derivations.

The following part discusses the system in detail with regards to the respective sub-systems and domains, thereby commenting of the engineering feasibility. The third part draws on from the second one, to present the cost analysis, deriving the cost of unit biomass. The fourth part is dedicated to the market analysis based on the findings of the previous two parts. Here the market segmentation, the SWOT analysis and the market opportunities as well as the market share for different application have been discussed. The last part summarises the result, presents a list of research questions and concludes this work.

Part II

System Design

In order to assess the market opportunities of vertical farms, one should find a market for the products grown in such a farm. Therefore, one should find out how much it costs to produce crops in vertical farms and whether such produces can compete with conventionally grown produces in terms of price. Although the carbon footprint of such produce is lower, post harvest costs are lower, quantifying these costs require imposition of pigouvian taxes on fruits and vegetables on the supermarket shelves. Since this is a monumental research endeavour, definitely beyond the scope of a master thesis, it is appropriate to concentrate on the cost comparison method. With this, one can argue that places where the price of crops grown in Vertical farms are less or at least same as the price of crops grown conventionally, are the places where such technology may find home. For that matter, a concurrent engineering study was conceived at the DLR-ISS in Bremen, where the cost of producing a kilo gram of mixed salad in a VF was worked out. In the following chapters the tentative design for a VF is being presented. It has been arrived at, through a brainstorming session involving 11 engineers and biologists. It is not the only possible design but a close approximation of a realistic one, which helps in making assumptions about the requirements and drawing cost estimations.

Figure 3.1.1: Rendering of the Vertical farm in Berlin

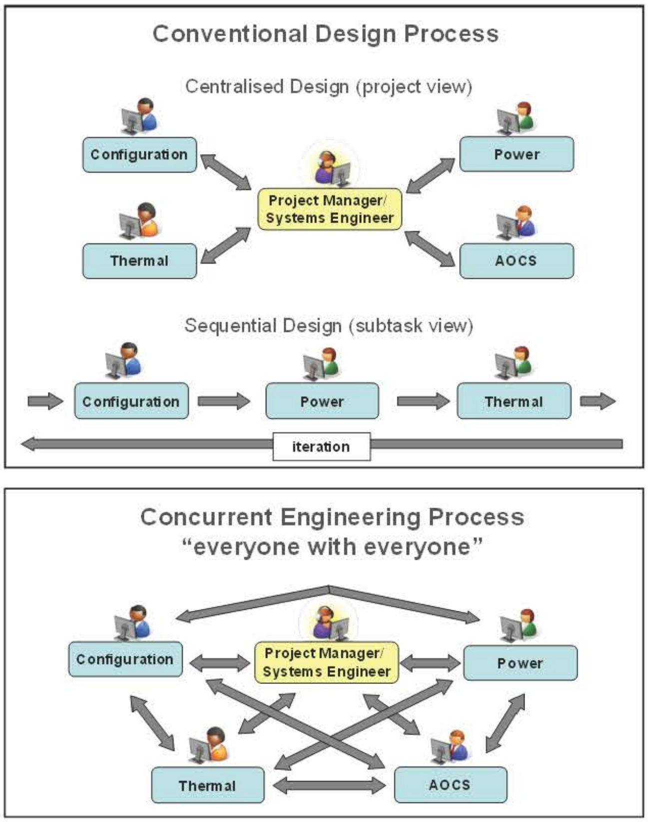
Chapter 4

Concurrent Engineering Study

To investigate and define the technical concept of a Vertical Farm, a Concurrent Engineering (CE) Study at DLR Bremen was performed. The CE-study comprised the analysis and the development of all subsystems necessary for a VF, to arrive at an estimation of the cost of producing an unit of biomass.

The applied Concurrent Engineering (CE) process is based on the optimization of the conventional established design process characterized by centralized and sequential engineering (see Figure: 4.0.1 top). Simultaneous presence of all relevant discipline's specialist within one location and the utilization of a common data handling tool enable efficient communication among the set of integrated subsystems (see Figure 4.2.2).

Figure 4.0.1: The Concurrent Design approach compared to projections of conventional design process



4.1 Objective: Cost estimation

The technologies required for the Vertical Farm are already available. Until now, however, there has been no study to design a Vertical Farm and determine the costs and earnings associated with it. The objective of this study, therefore, is to determine the economic feasibility of a Vertical Farm.

To achieve this goal it is necessary to analyse all the different capital and operating costs, such as building costs or power and equipment costs, which are needed for the Vertical Farm to function. By comparing the total costs with the production of the Vertical Farm, it is possible to determine an average price for the food produced in the Vertical Farm.

While the Vertical Farm provides clear advantages over traditional agriculture by offering the possibility of increased grow area and reduced transport costs, the eventual success still depends on the price difference between food produced in fields and conventional greenhouses and food prepared in a Vertical Farm. This concurrent engineering study is aimed at designing a vertical farming system over an area of 2500 m^2 or 0.25 ha, and calculating the annual cost of growing a mixture of 10 crops and a fish species in it. In conventional agriculture plants get four most important requirements without consideration for cost. They are: Space (This includes soil and growing space); Water and soluble nutrients (mostly received through rainfall and soil water); Gases (mainly carbon dioxide and oxygen); Light (for photosynthesis).

In case of vertical farming these ubiquitous factors must be provided at a cost. Therefore it is imperative that a business proposition of this nature should go for cost minimisation. Profit maximisation, a classical assumption of objective function in production economics has to be overlooked since at this stage of market analysis, factor or product prices can not be ascertained. For that matter, heuristics was used to ascertain the exact proportion of area to be allotted to each crop. The results are discussed in the respective chapters.

4.2 Plan for Advanced Study Group

The VF is planned to have the following process flow as shown in Figure 4.2.1. It consists of a number of system loops, like the ones for nutrients, water, heating, CO_2, whereby these factors are recycled. In addition it also requires external inputs in terms of the above factors as well as seeds, fish fingerlings, feeds and most importantly power. The outputs are mainly processed and packed edible plant and fish mass as well as slurry from digestion of inedible biomass.

The CE study had the group composition seen in Figure 4.2.2.

Figure 4.2.1: Process flow

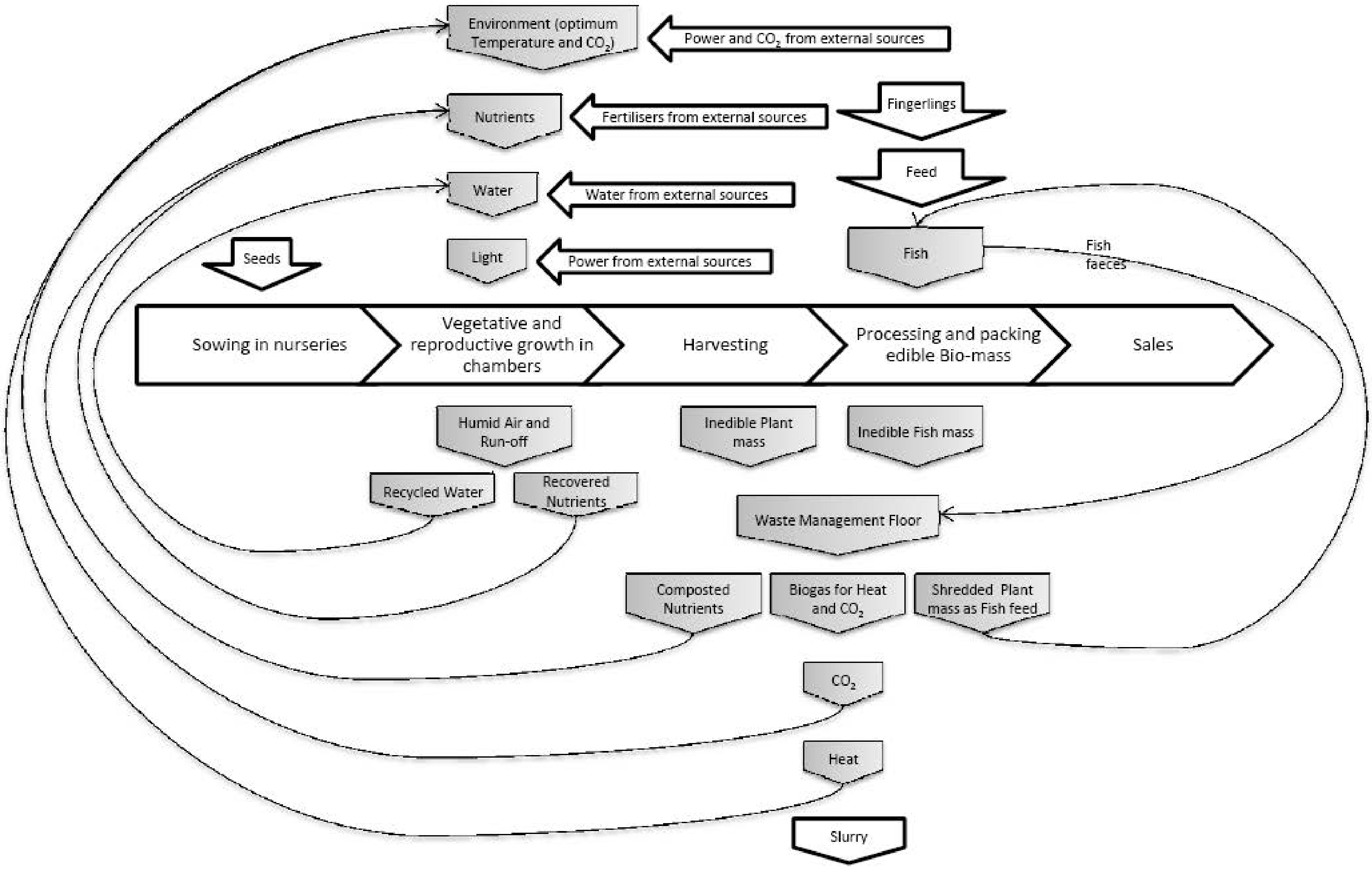
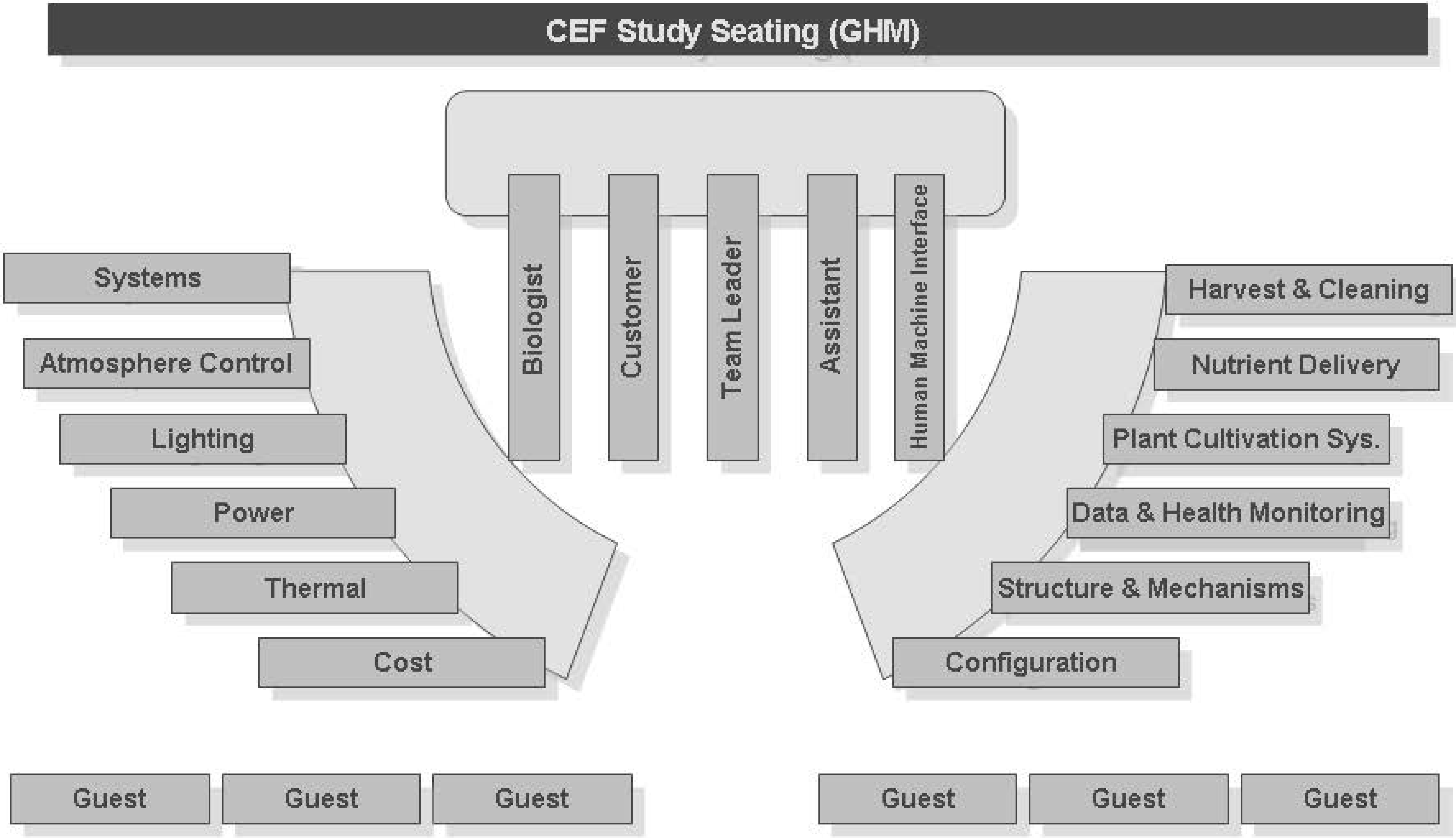


Figure 4.2.2: Concurrent Engineering Study group plan



Chapter 5

Systems

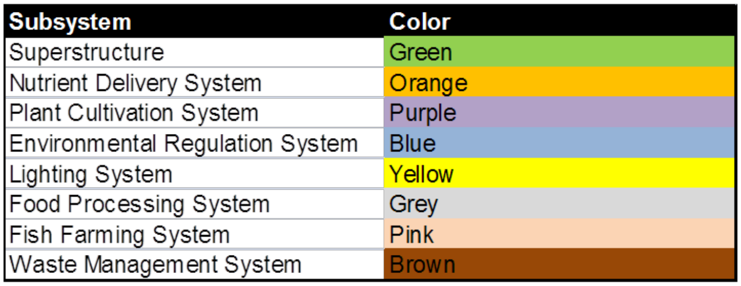
The start of any CE-study or design should be to determine the functions the final design should have and how these functions can best be grouped together in specific systems. This is especially important for CE-studies or design projects carried out by multiple people, since different people will be working on different systems. If the systems are not properly defined, there is an increased risk that the final system designs, when combined, do not yield the desired overall performance. Hence, this chapter presents the initial system analysis for the Vertical Farm. A Functional Breakdown is given, as well as Subsystem and Interface Definitions.

5.1 Requirements

The primary function of the Vertical Farm is to produce edible biomass, either through crop cultivation or animal husbandry. Based on this requirement on the Vertical Farm, it is immediately possible to determine several other requirements. For example, it will be necessary to provide food (for animals) and nutrients (for crops) in specific quantities at precise times. Additionally, it will be necessary to manage the by-products of the edible biomass production, such as inedible biomass or trace gases.

A (partial) overview of the different functions which need to be fulfilled by the Vertical Farm, in order to produce edible biomass, can be found in the Functional Breakdown in Figure 5.1.1. The functions shown in Figure 5.1.1 are color-coded according to the subsystem which will handle that specific task. The subsystems which have been defined for study in this CEF-study can be seen in Table 5.1. This is only one of various possible system breakdowns which can be made for the Vertical Farm. While the system breakdown, as shown in Table 1, makes it possible to divide the design team into smaller teams, with each team being responsible for a specific subsystem, it also brings a bit more complexity.

Table 5.1: System Breakdown for the Vertical Farm



Subsystem	Color
Superstructure	Green
Nutrient Delivery System	Orange
Plant Cultivation System	Purple
Environmental Regulation System	Blue
Lighting System	Yellow
Food Processing System	Grey
Fish Farming System	Pink
Waste Management System	Brown

It is not possible to design each subsystem separately, put the design together and end up with a fully-functioning, optimized design for the Vertical Farm. During the design process the different teams need to work closely together to deal with the so called interfaces between the different subsystems. These interfaces are design aspects of one subsystem which affect another subsystem. An obvious example is the superstructure subsystem. An increase or decrease in footprint area or floor height of the building will impact every other subsystem, since it defines the available space for equipment and biomass production. Identifying these interfaces is therefore a very important aspect of the initial design project. For the Vertical Farm the Interface Definitions can be found in the N^2-chart in Figure 5.1.2. Note that since the Interface Definitions are dependent on subsystems, it may vary depending on the specific system breakdown which is used.

Figure 5.1.1: Functional Breakdown for the Vertical Farm

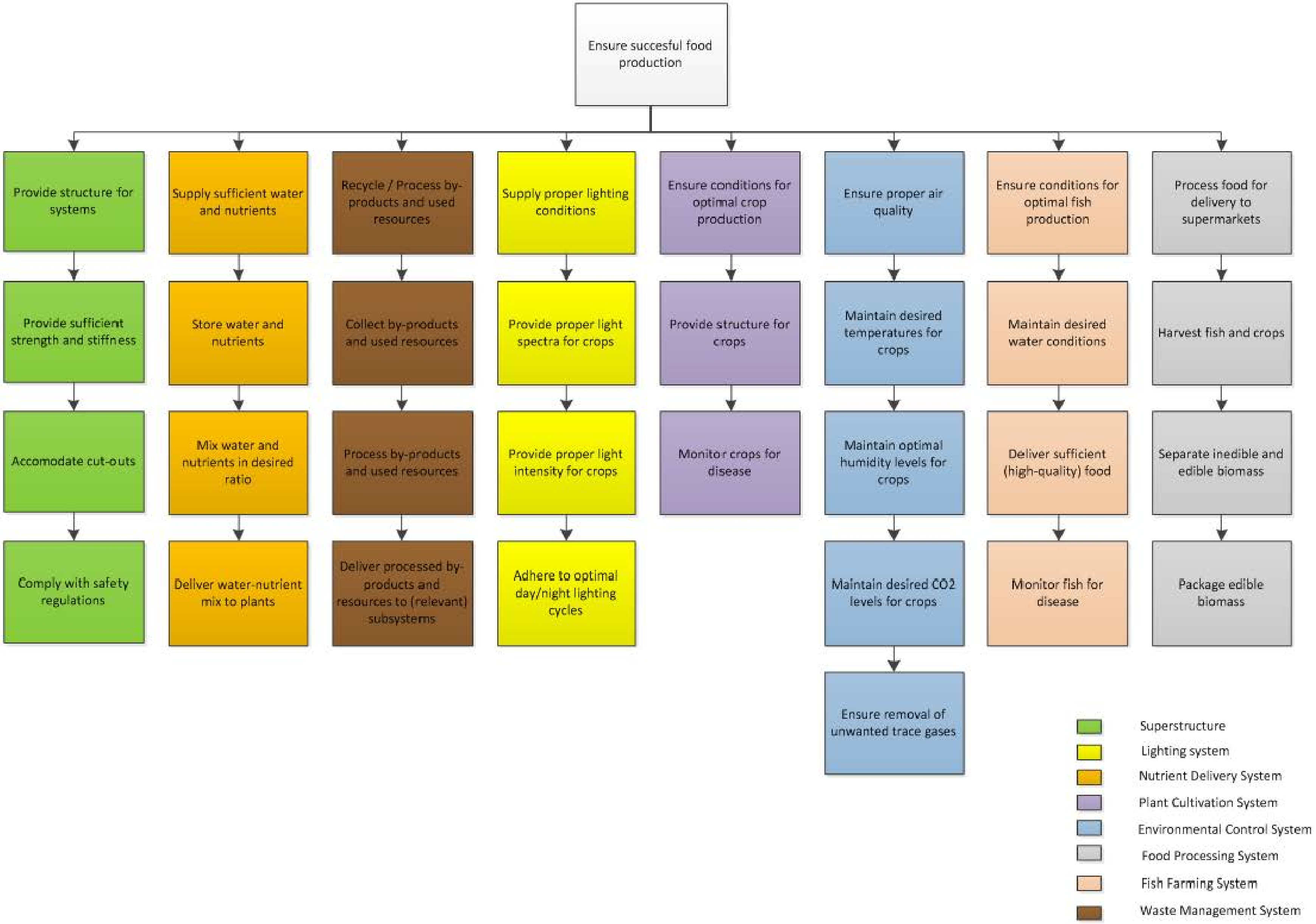
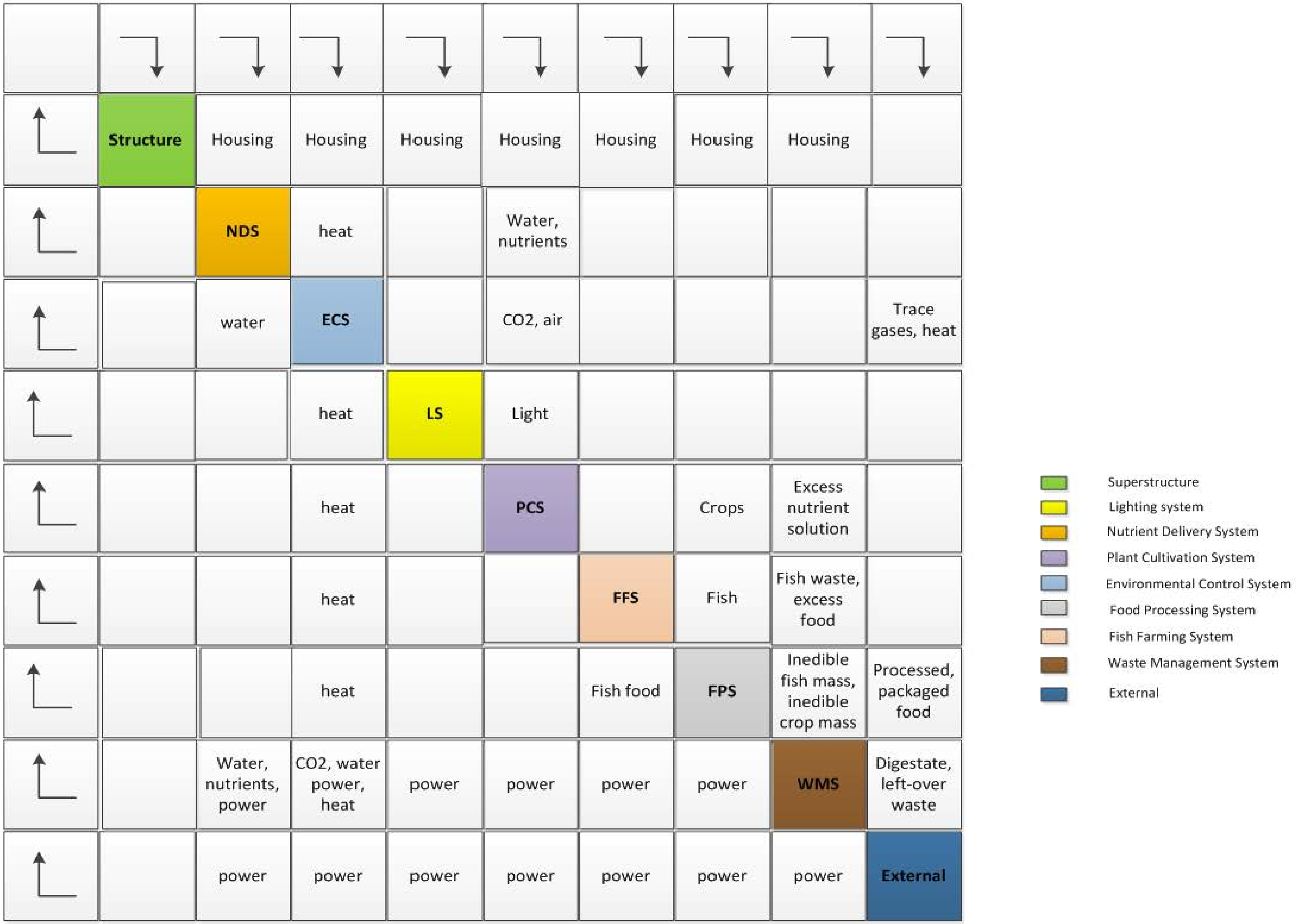


Figure 5.1.2: N^2-chart Interface Definitions for the Vertical Farm



	↴	↴	↴	↴	↴	↴	↴	↴	↴
↱	**Structure**	Housing	Housing	Housing	Housing	Housing	Housing	Housing	
↱		**NDS**	heat		Water, nutrients				
↱		water	**ECS**		CO2, air				Trace gases, heat
↱			heat	**LS**	Light				
↱			heat		**PCS**		Crops	Excess nutrient solution	
↱			heat			**FFS**	Fish	Fish waste, excess food	
↱			heat			Fish food	**FPS**	Inedible fish mass, inedible crop mass	Processed, packaged food
↱		Water, nutrients, power	CO2, water power, heat	power	power	power	power	**WMS**	Digestate, left-over waste
↱		power	power	power	power	power	power	power	**External**

🟩	Superstructure
🟨	Lighting system
🟧	Nutrient Delivery System
🟪	Plant Cultivation System
🟦	Environmental Control System
⬜	Food Processing System
🟠	Fish Farming System
🟫	Waste Management System
🟦	External

Chapter 6

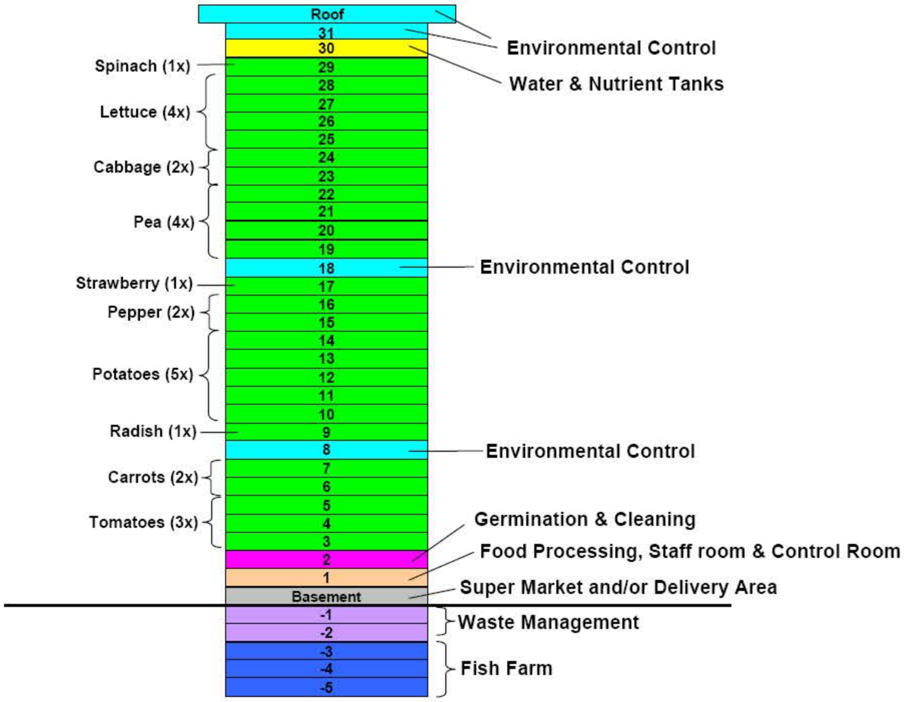
Superstructure

In order to support this system the tower is planned to have the following configuration. A total of 37 floors, with 25 of them solely for the purpose of crop production and 3 for aquaculture. Further 3 uniformly distributed floors are for environmental regulation and 2 in the basement for waste management. In addition there is one floor for cleaning of the growth trays, sowing and germination, one for packing and processing the plants and fish and one for sales and delivery at the basement. The detailed layouts of the floors has been discussed in designated chapters.

As can be seen in the N^2-chart in Figure 5.1.2, there are interfaces between the superstructure and every other subsystem of the Vertical Farm. The footprint area, the number of floors and the total building height are just a few of the parameters which are crucial in determining the costs and possible output of the Vertical Farm.

During this CEF-study no calculations were performed on the structural stiffness or moments of inertia. Instead some estimates were made, based on data from literature, about the building aspect ratio and the corresponding placement of structural elements.

Figure 6.0.1: Layout of the Vertical Farm



6.1 Dimensions

Based on requirements from other subsystems, the dimensions of the base were selected to be 44 by 44 meters for the exterior structure. Only the inner 40 by 40 meters were available to the subsystems for their design calculations, while the remaining 2 meters on all sides was reserved for columns and air ducts leading from the plant cultivation floors to the environmental control floors.

The Vertical Farm should have an above average floor-to-ceiling height to better accommodate multiple stacks of crops per floor. Thus a floor-to-ceiling height of 3.5 meters was selected. The ceiling thickness value was taken to be 1 meter, leading to a floor-to-floor height of 4.5 meters. The structural material for the floor was selected to be reinforced concrete. With 37 floors, the total height of the building came out at 167.5 meters.

6.2 Design elements

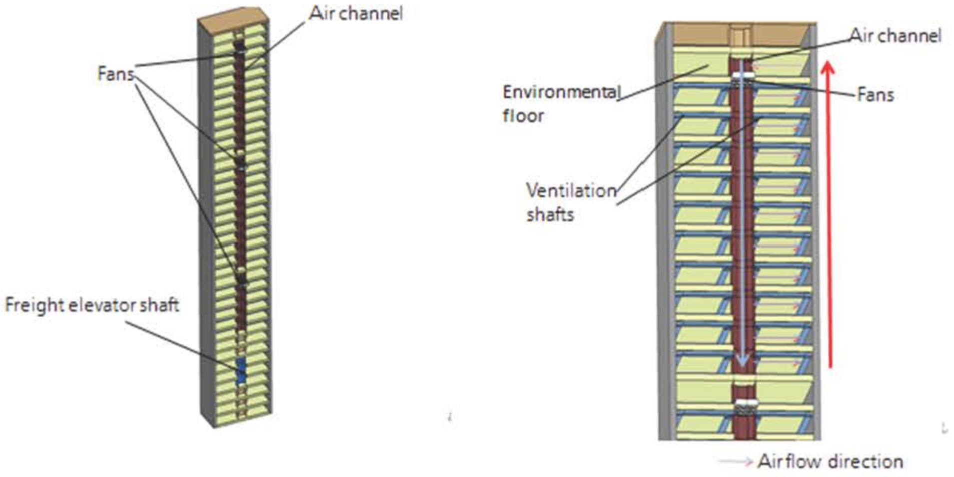
A total building height of 167.5 meters, with a length (and width) of 44 meters, gives an aspect ratio of 3.81. While this is quite low for high-rise buildings, with the Jin Mao Tower having an aspect ratio of 7.8 [38] for example, it does mean that the structural design can be rather straightforward. From [38] it can be found that for aspect ratios of 7 or lower, a building does not necessarily need a central structural core. Instead exterior tube frames or braced tube systems will be able to provide sufficient structural support.

However, since no calculations were carried out, it was felt that it would be better to have a combination of (somewhat) central, internal columns and columns at the outer edges of the building. Aside from the column placement, the superstructure will have to contain elevators and stairs to allow personnel to move between floors. Since the building has to adhere to safety regulations, it was decided to have two sets of stairs and elevators. This way, the distance between any particular place on a floor and the staircase is less than the maximum allowable distance. Furthermore, based on the United Nations' requirements on (emergency) staircases [74], specific dimensions for the stair well could be determined. It was assumed for simplicity that the elevator shaft would be equal to the stairwell in size. A more detailed design should determine how many elevators are required to deal with the personnel demands, and whether or not the elevator shaft size is sufficient.

A large freight elevator shaft was placed in the centre of the building, running from the entrance floor down to the Waste Management Floors. This freight elevator is big enough to allow a forklift truck to enter and exit the elevator, allowing for waste to be transported out of the building or between the Waste Management Floors, see Figure 6.2.1a. The freight elevator shaft is the same size as the large air channels running from the Environmental Control Floors to the Plant Cultivation Floors. Air flows down these channels and into the different Plant Cultivation Floors and is guided into the Plant Grow Units through air ducts. After passing through the Plant Grow Units, the air flows into a central duct which leads the air out into ducts at the sides of the building which guide the flow back up to the

Environmental Control Floor, see Figure 6.2.1b.

Figure 6.2.1: Section view of the inside of the Vertical Farm



(a) Elevator Shafts

(b) Air Flow

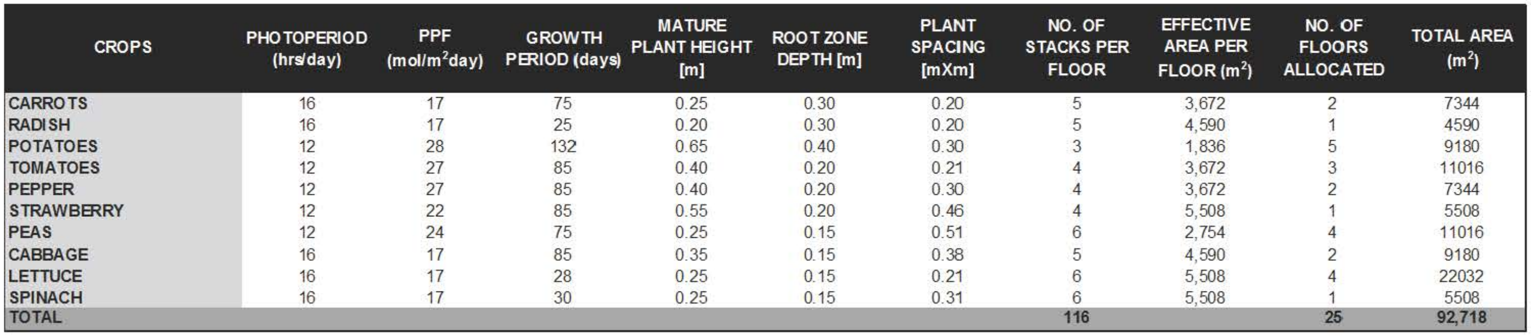
Chapter 7

Agricultural Sub-system

The summary of the system and related assumptions are to be found in Table 7.1. It is limited by the building parameters. A list of 10 plants (shown in the first column) was chosen for calculation of yields produced in VF building. Criteria for selection were availability of parametric data for cultivation and yield in artificial environment and a relatively high biomass output [49, 86, 85, 44, 63, 14, 16]. Besides, the cost of producing a palette of product instead of a monoculture enables the reader to make rough assumptions about the cost of producing one or a subset of these crops.

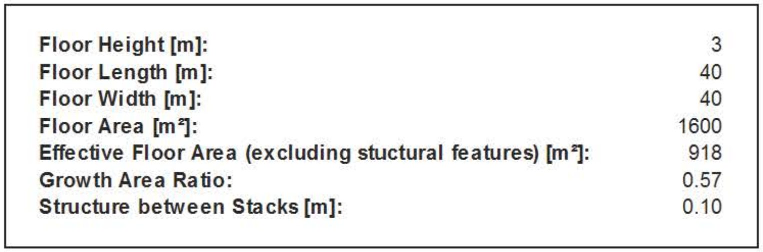
The plants are classified by morphological features, plant shape and their requirements in terms of volume and area into 4 categories namely: root/tuber crops (carrots, radish, potato), fruit crops (tomato, pepper, strawberry), vines (peas) and leafy vegetables (cabbage, lettuce, spinach). The second column gives information about observed growth periods for each plant (cultivar initiation to harvest), which gives us an overview of the time dimension and number of harvests one can draw per year. This greatly influences the growth cycles. The following columns are about the space requirement and space allocation per crop. The respective planting areas per floor (multiple of effective floor area and the number of possible stacks) is to be found in column 6. Planting area per crop is defined mainly by number of floors and number of plant shelves allocated, dependent on the space requirement of the plants.

Table 7.1: Space-time requirements of crops



CROPS	PHOTOPERIOD (hrs/day)	PPF (mol/m^2day)	GROWTH PERIOD (days)	MATURE PLANT HEIGHT [m]	ROOT ZONE DEPTH [m]	PLANT SPACING [mXm]	NO. OF STACKS PER FLOOR	EFFECTIVE AREA PER FLOOR (m^2)	NO. OF FLOORS ALLOCATED	TOTAL AREA (m^2)
CARROTS	16	17	75	0.25	0.30	0.20	5	3,672	2	7344
RADISH	16	17	25	0.20	0.30	0.20	5	4,590	1	4590
POTATOES	12	28	132	0.65	0.40	0.30	3	1,836	5	9180
TOMATOES	12	27	85	0.40	0.20	0.21	4	3,672	3	11016
PEPPER	12	27	85	0.40	0.20	0.30	4	3,672	2	7344
STRAWBERRY	12	22	85	0.55	0.20	0.46	4	5,508	1	5508
PEAS	12	24	75	0.25	0.15	0.51	6	2,754	4	11016
CABBAGE	16	17	85	0.35	0.15	0.38	5	4,590	2	9180
LETTUCE	16	17	28	0.25	0.15	0.21	6	5,508	4	22032
SPINACH	16	17	30	0.25	0.15	0.31	6	5,508	1	5508
TOTAL							116		25	92,718

Source:[49]



Floor Height [m]:	3
Floor Length [m]:	40
Floor Width [m]:	40
Floor Area [m^2]:	1600
Effective Floor Area (excluding stuctural features) [m^2]:	918
Growth Area Ratio:	0.57
Structure between Stacks [m]:	0.10

7.1 System Description

The Vertical Farm has to provide the proper conditions for the different crop types to grow from seeds until the plants can be harvested. It is envisioned that the initial germination of the seeds is done on a specialized Germination Floor, see Figure 9, while the later stages of the plant life cycles take place on the Plant Cultivation Floors.

7.1.1 Germination Floor

The Germination Floor, as shown in Figure 7.1.1, contains 12 Germination Units. There is no exact calculation on the number of seeds which can be placed in one Germination Unit at a time, but it is estimated that 12 Germination Units should be able to supply sufficient seeds for the Plant Cultivation Floors to operate at full capacity.

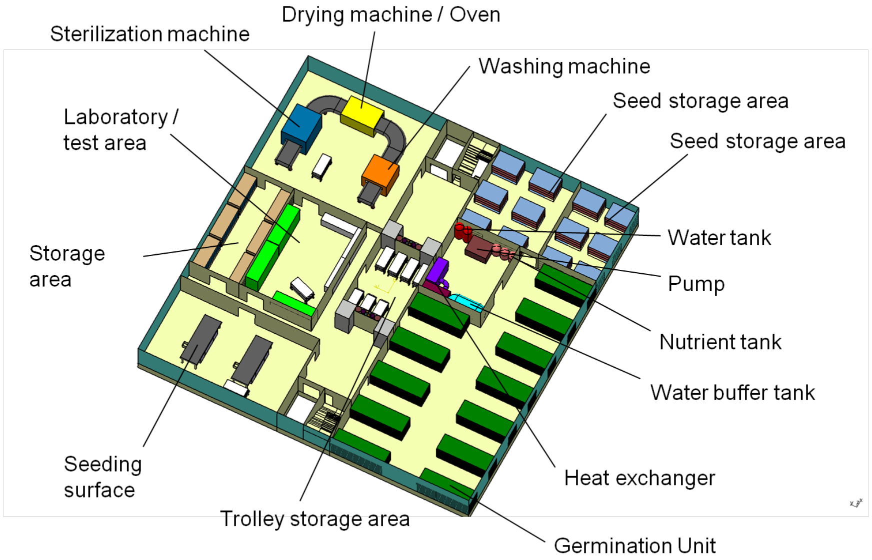
Aside from the Germination Units, there are two rooms for seed storage. These two rooms could, if necessary, maintain different environmental conditions to optimally preserve the seeds. It is estimated that, based on the size of plant seeds, these two rooms should be able to hold enough seeds for several years of plant cultivation in the Vertical Farm.

Between the germination area and the seed storage area there is a room which houses the nutrient and water tanks, along with some pumps and heat exchangers. This room controls the conditions in the Germination Unit, ensuring that the seeds are kept at the required conditions.

The Germination Floor also has a room for trolley storage and seeding of the grow pallets. The trolleys can be used to move seeds or grow pallets from room to room, or even to other floors, while the seeding area is used to place seeds on grow pallets at predetermined distances.

The floor has another additional storage room, a laboratory area and a cleaning area. The storage room is used to store grow pallets and grow lids, as well as any equipment which may be required. The laboratory area is a room where seed and plant specimens can be examined, while the cleaning area is present to clean equipment and prevent contamination and sources of disease from getting in contact with the plants.

Figure 7.1.1: Layout of Germination and Cleaning Floor

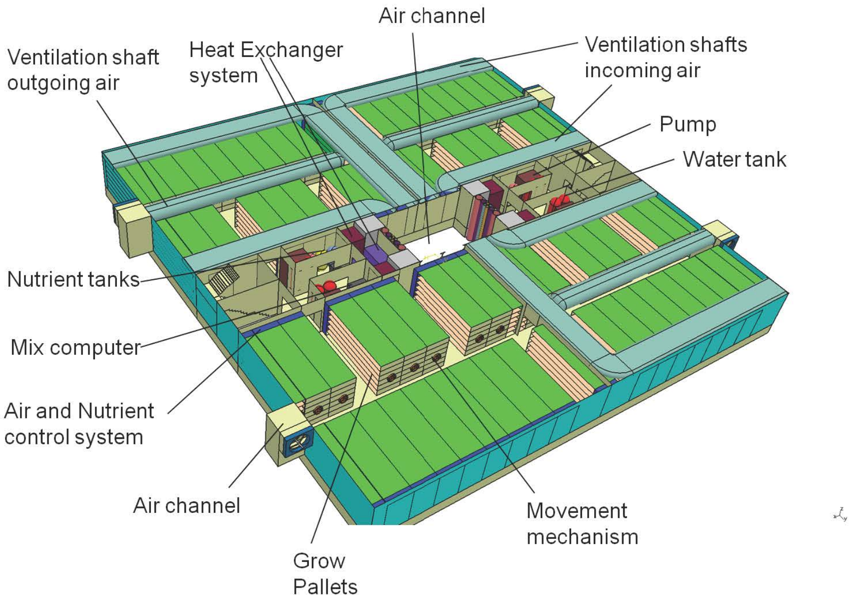


7.1.2 Plant Cultivation Floor

For the Plant Cultivation Floors a plant growth area plan has been drawn based on the philosophy of having eight cultivation stages which can be harvested at different times. The eight stages will spread out the crop production over time, leading to a more uniform daily yield.

The shelves for the plant growth are comprised of both fixed and moving platforms. The moving platforms are 14.5 m^2 and the fixed platforms 7.25 m^2. Calculation of the effective area based on the floor plan as shown in Figure 11.1.1a gives a total area factor of 0.6125, meaning that about 61% of the total floor area is used for plant cultivation. A CATIA drawing of the plant production floor, including air ducts and nutrient delivery system equipment can be found in Figure 6.2.1a.

Figure 7.1.2: Layout for Crop Floors



7.2 Edible plant biomass

In Table 7.2 production capacity for the VF is summarized. In order to avoid peaks and troughs of labour requirement, production is planned in lagged cycles. Each floor is divided into 8 chambers, and they are planted with the same crop at 7 days interval. This also ensures a steady supply of the produce to the centres of demand, without having to shoulder the responsibility of storing and refrigeration. A steady supply also makes it possible to directly sell value added products.

The entire estimation is based on the daily yield of edible plant mass (column 5), in addition to the cropping pattern. The second column gives a number of chambers harvested per year per crop. The third column shows the edible biomass output per chamber per crop. The fourth columns presents the yield values per year with conservative hydroponic cultivation. Increased yields, derived from advanced cultivation methods as elevated CO_2-levels and aeroponics are reported in the last two columns. The rest are derived from the other values, gives the reader an overview of the production capacity.

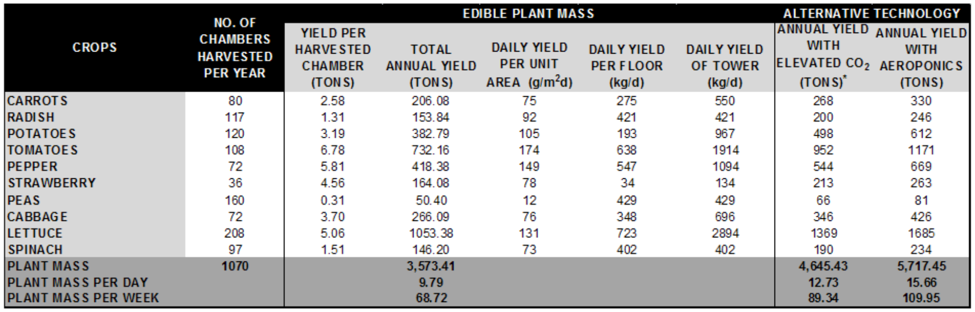
Additional increases in yield through the use of advanced cultivation methods (CO_2 – elevation, optimized aeroponic cultivation) are based on the literature reported in Table 7.2a and are calculated by multiplying yields with an estimated factor (1.3 for elevated CO_2, 1.4 for aeroponics). The calculated total yield of edible plant biomass is 3573.41 tons per year for the whole building (using hydroponics [49]).

In agriculture yield efficiency (usable biomass/total biomass) can be defined by the harvest index (HI). Estimations for the complete cultivar composition of the VF gave a HI-value about 0.6, which means 60% of total biomass is edible.

7.3 Inedible plant biomass

Inedible plant biomass is the amount of biomass that can not be processed for human consumption. For the VF cultivars, the amount of inedible biomass is estimated as 40% of total biomass output. Table 7.3 reports the inedible biomasses produced per plant, per harvest event and per year. These calculations are also based on the daily yield of inedible plant biomass (column 4), in addition to the cropping pattern. These masses have multiple uses. In this system they are handled within the tower. They are firstly used as feed for the tilapia, secondly they are composted to enrich nutrient solution for the crop cultivation, they are further digested to produce bio-gas for heat and CO_2 generation. In addition they may be considered for elevating the level of CO_2 in the plant growth chambers.

Table 7.2: Edible Plant-mass Production



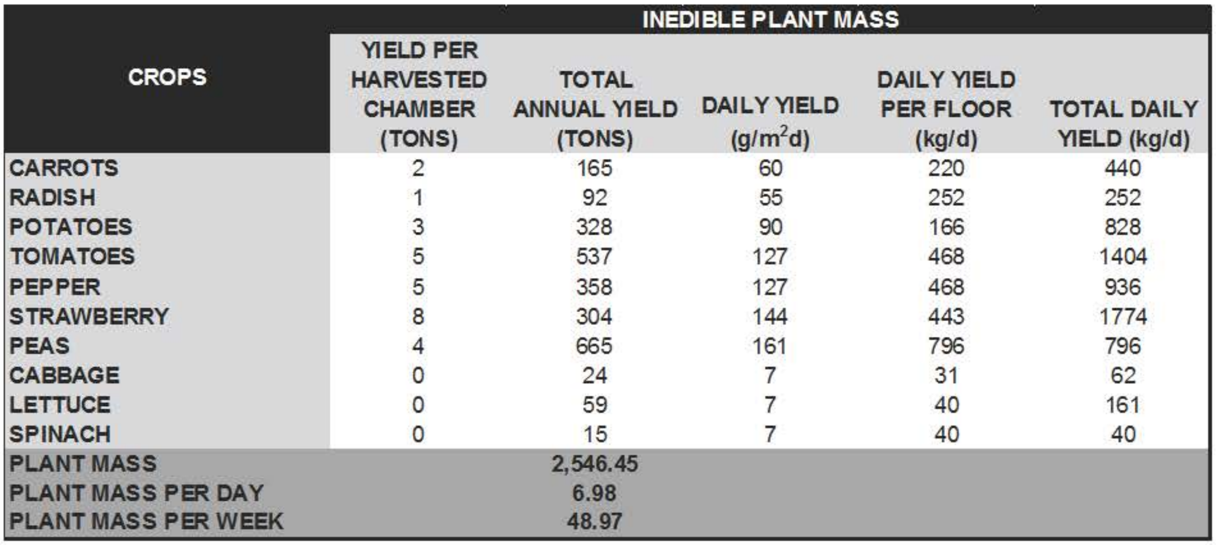
CROPS	NO. OF CHAMBERS HARVESTED PER YEAR	EDIBLE PLANT MASS					ALTERNATIVE TECHNOLOGY	
		YIELD PER HARVESTED CHAMBER (TONS)	TOTAL ANNUAL YIELD (TONS)	DAILY YIELD PER UNIT AREA (g/m^2d)	DAILY YIELD PER FLOOR (kg/d)	DAILY YIELD OF TOWER (kg/d)	ANNUAL YIELD WITH ELEVATED CO_2 (TONS)*	ANNUAL YIELD WITH AEROPONICS (TONS)
CARROTS	80	2.58	206.08	75	275	550	268	330
RADISH	117	1.31	153.84	92	421	421	200	246
POTATOES	120	3.19	382.79	105	193	967	498	612
TOMATOES	108	6.78	732.16	174	638	1914	952	1171
PEPPER	72	5.81	418.38	149	547	1094	544	669
STRAWBERRY	36	4.56	164.08	78	34	134	213	263
PEAS	160	0.31	50.40	12	429	429	66	81
CABBAGE	72	3.70	266.09	76	348	696	346	426
LETTUCE	208	5.06	1053.38	131	723	2894	1369	1685
SPINACH	97	1.51	146.20	73	402	402	190	234
PLANT MASS	**1070**		**3,573.41**				**4,645.43**	**5,717.45**
PLANT MASS PER DAY			**9.79**				**12.73**	**15.66**
PLANT MASS PER WEEK			**68.72**				**89.34**	**109.95**

Source: [49]

(a) *Literature on effect of elevation of CO_2concentration

Source	Elevation levels	Observed increase in plant biomass
[44]	300 (ambient) to 600 µmol/mol	32%
[63]	400 (ambient) to 800 µmol/mol	33- 79%
[85]	500 (ambient) to 1000 µmol/mol	20-50%
[14]	340 (ambient) to 1200 µmol/mol	30-40%
[16]	350 (ambient) to 700 µmol7mol	25-35%
[86]	328 (ambient)to 531 µmol/mol	34%

Table 7.3: Inedible Plant biomass Production



CROPS	INEDIBLE PLANT MASS				
	YIELD PER HARVESTED CHAMBER (TONS)	TOTAL ANNUAL YIELD (TONS)	DAILY YIELD (g/m^2d)	DAILY YIELD PER FLOOR (kg/d)	TOTAL DAILY YIELD (kg/d)
CARROTS	2	165	60	220	440
RADISH	1	92	55	252	252
POTATOES	3	328	90	166	828
TOMATOES	5	537	127	468	1404
PEPPER	5	358	127	468	936
STRAWBERRY	8	304	144	443	1774
PEAS	4	665	161	796	796
CABBAGE	0	24	7	31	62
LETTUCE	0	59	7	40	161
SPINACH	0	15	7	40	40
PLANT MASS		2,546.45			
PLANT MASS PER DAY		6.98			
PLANT MASS PER WEEK		48.97			

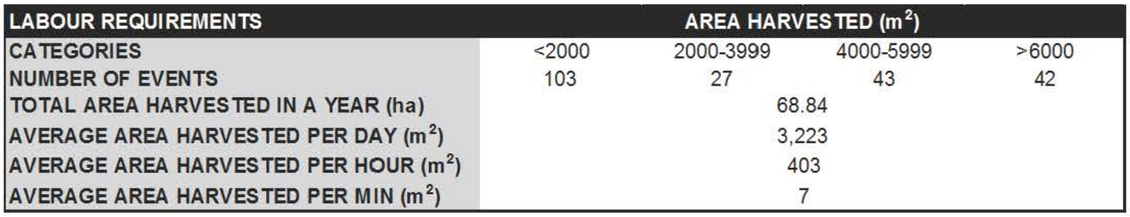
Source: [49]

7.4 Labour Requirements

The aforementioned cropping cycle creates a continuous sowing and harvesting loop. The total number of sowing and harvest events is 215 in 365 days in which a total of 688,385.25 m^2 or 69 ha is sown and harvested every year. Clashing events in harvest, when different crop cultivars have to be harvested at the same day, may increase work intensities for some days. However since this does not require any specialised skill set, labour force from other departments can be pooled in during such peak periods. The cycle assumes every floor to be planted in 8 intervals, if this is replicated for each crop by multiplying the chambers per floor by the number of floors, the work load distribution would be even more uniform. For example, potato is grown in 5 floors and it is assumed that every time 5 chambers (1 in each floor) are sown and harvested per event. If the cycle is extended by sowing only on chamber in 7 days interval, the production and labour requirement will be both more uniform.

In order to keep the labour requirements economical, we consider the area to be harvested per event. As seen in Table 7.4, the work load is classified on the basis of area harvested. So there are 103 events when less than 2000 m^2 and only 42 events when more than 6000 m^2 of total stack area are harvested. A weighted average is being made to arrive at the area cultivated on an average. To handle a stack area of 403 m^2 per hour (harvest and preparation of new seed trays) an estimated work force of 6 – 10 workers (based on 8 h work time per day) should suffice. For peak periods (>4000 m^2) a inter-departmental transfer of personnel may be planned.

Table 7.4: Labour requirement

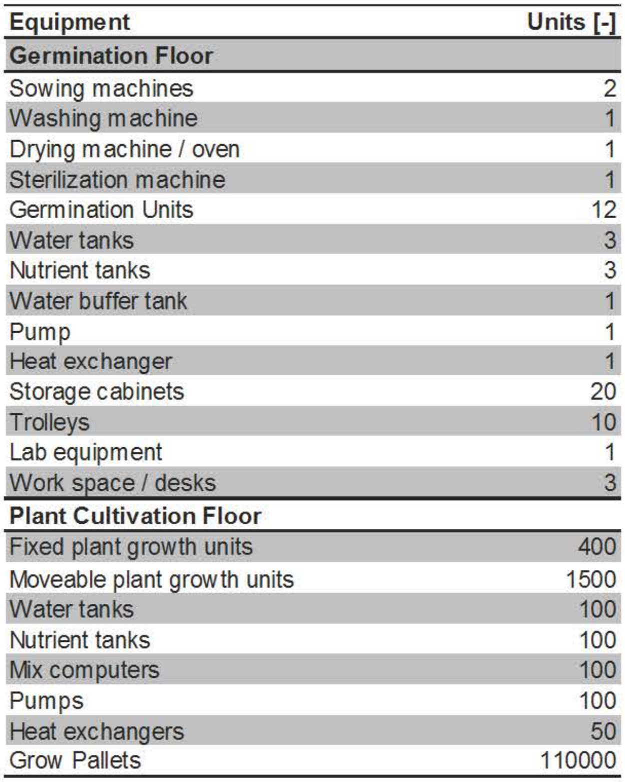


LABOUR REQUIREMENTS	AREA HARVESTED (m^2)			
CATEGORIES	<2000	2000-3999	4000-5999	>6000
NUMBER OF EVENTS	103	27	43	42
TOTAL AREA HARVESTED IN A YEAR (ha)	68.84			
AVERAGE AREA HARVESTED PER DAY (m^2)	3,223			
AVERAGE AREA HARVESTED PER HOUR (m^2)	403			
AVERAGE AREA HARVESTED PER MIN (m^2)	7			

7.5 List of Equipments

The Germination and Cleaning Floor, along with the 25 Plant Cultivation Floors produce about 4000 tons of edible crop biomass per year. To achieve this, certain equipment needs to be present in the Vertical Farm. For the Germination and Cleaning Floor, for example, a number of Germination Units are required, while the Plant Cultivation Floors need Grow Units, among other things. It is possible to determine the total set-up cost of these floors, by creating a list of required equipment and estimating the cost as shown in the Table: 7.5.

Table 7.5: List of Equipments for agricultural sub-system



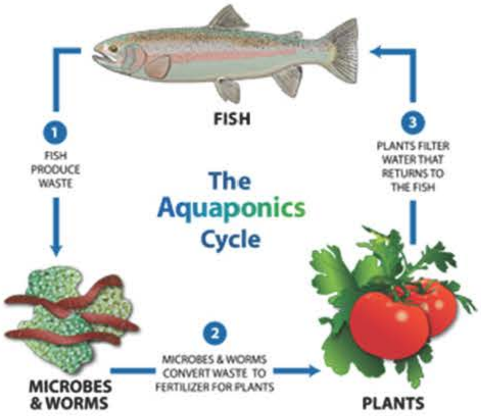
Equipment	**Units [-]**
Germination Floor	
Sowing machines	2
Washing machine	1
Drying machine / oven	1
Sterilization machine	1
Germination Units	12
Water tanks	3
Nutrient tanks	3
Water buffer tank	1
Pump	1
Heat exchanger	1
Storage cabinets	20
Trolleys	10
Lab equipment	1
Work space / desks	3
Plant Cultivation Floor	
Fixed plant growth units	400
Moveable plant growth units	1500
Water tanks	100
Nutrient tanks	100
Mix computers	100
Pumps	100
Heat exchangers	50
Grow Pallets	110000

Chapter 8

Aquacultural Sub-system

The fish farm serves as waste disposal, nutrient source and food production within the VF. It will add to the efficiency of the farm by utilizing irrigated water from plants as well as plant waste to create food in the form of edible fish biomass. This process is also often called Aquaponics and is illustrated in Figure 8.0.1.

Figure 8.0.1: Aquaponics cycle



8.1 Fish selection

There are several species of fish which are used throughout the world within aquaculture, most notably carp, catfish, salmon and tilapia. Of these fish, Tilapia has been chosen because of the following advantages:

- Feed Tilapia is able to consume a wide range of feed, which makes it very adaptable to a VF
- Water temperature – The tropical water temperature required by tilapia is ideal for a VF as heat run-off from LED lighting can be used as heating for the tanks
- Growth speed Tilapia fish are very efficient in transforming feed into animal protein, the feed/fish mass ratio ranges from 1.5 to 2 depending on water conditions and feed quality
- Mercury levels- Tilapia have natural low mercury levels
- Taste The moderate fish taste of tilapia makes it a widely eaten and acceptable taste

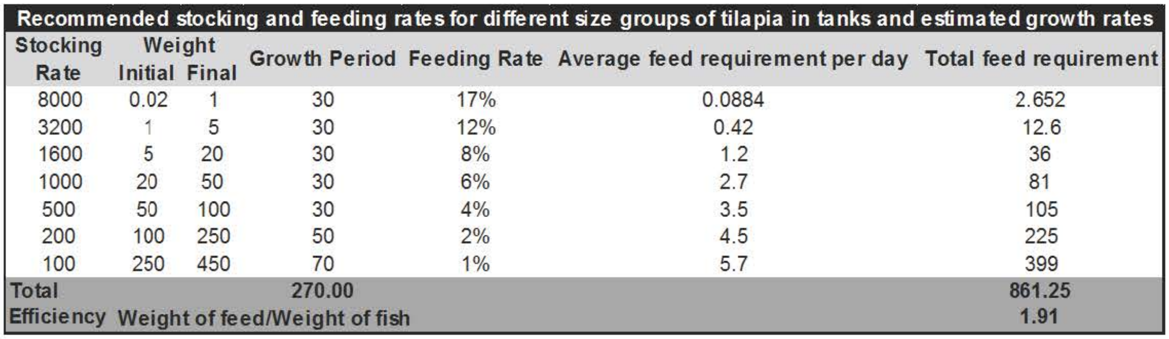
Some drawbacks that should be coped with include:

- Low levels of omega-3 and high levels of omega-6 make the fish relatively unhealthy
- Intensive farming requires high protein food which is not present within the inedible mass produced by the agricultural part of the VF

8.2 Baseline Design

The design is based on a balanced production cycle, which aims to optimize the production between the different maturity stages and corresponding tanks. The different feeding requirements per maturity stage are illustrated in the Table: 8.1.

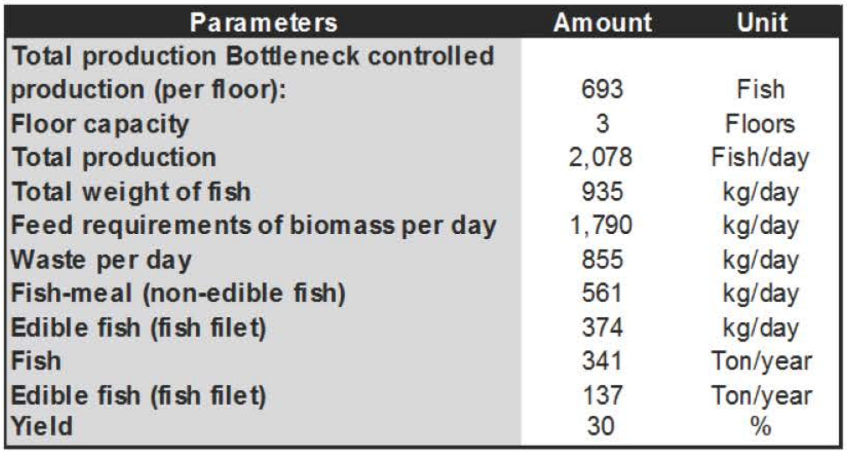
Table 8.1: Tilapia feed requirements



Recommended stocking and feeding rates for different size groups of tilapia in tanks and estimated growth rates						
Stocking Rate	Weight Initial	Final	Growth Period	Feeding Rate	Average feed requirement per day	Total feed requirement
8000	0.02	1	30	17%	0.0884	2.652
3200	1	5	30	12%	0.42	12.6
1600	5	20	30	8%	1.2	36
1000	20	50	30	6%	2.7	81
500	50	100	30	4%	3.5	105
200	100	250	50	2%	4.5	225
100	250	450	70	1%	5.7	399
Total			**270.00**			**861.25**
Efficiency	**Weight of feed/Weight of fish**					**1.91**

To balance production and decrease handling cost, 5 different tanks size are chosen which are optimized to the desired production volume of close to 700 fish per day per floor (refer to Table 8.3). This requirement has led to the following floor layout and floor design (shown in Figure 8.2.1). The yield of edible and inedible fish biomass is tabulated in Table 8.2. It leads to a total estimated production of 341 tons of fish per year, with 137 tons of edible fish fillet (details are discussed in 15.2).

Table 8.2: Aquaculture yield



Parameters	Amount	Unit
Total production Bottleneck controlled production (per floor):	693	Fish
Floor capacity	3	Floors
Total production	2,078	Fish/day
Total weight of fish	935	kg/day
Feed requirements of biomass per day	1,790	kg/day
Waste per day	855	kg/day
Fish-meal (non-edible fish)	561	kg/day
Edible fish (fish filet)	374	kg/day
Fish	341	Ton/year
Edible fish (fish filet)	137	Ton/year
Yield	30	%

Figure 8.2.1: Layout of Fish floor

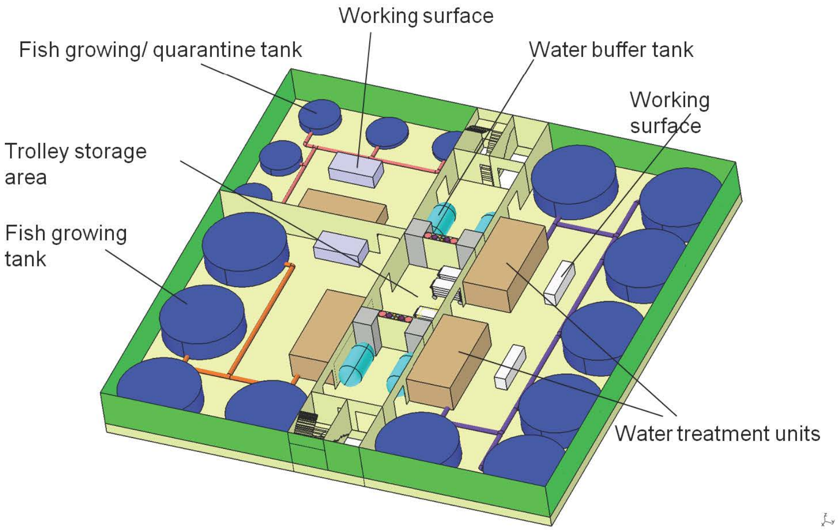
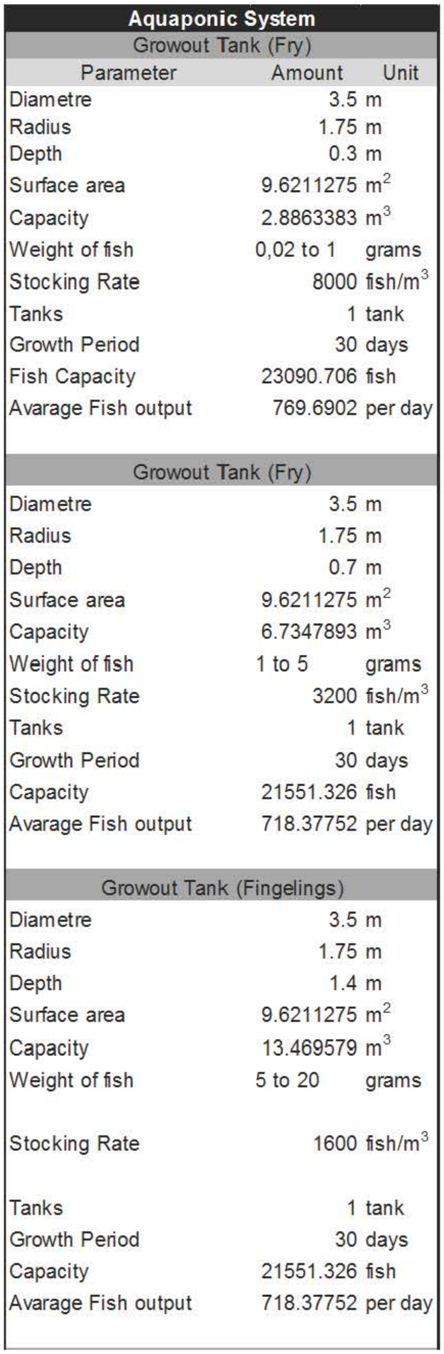
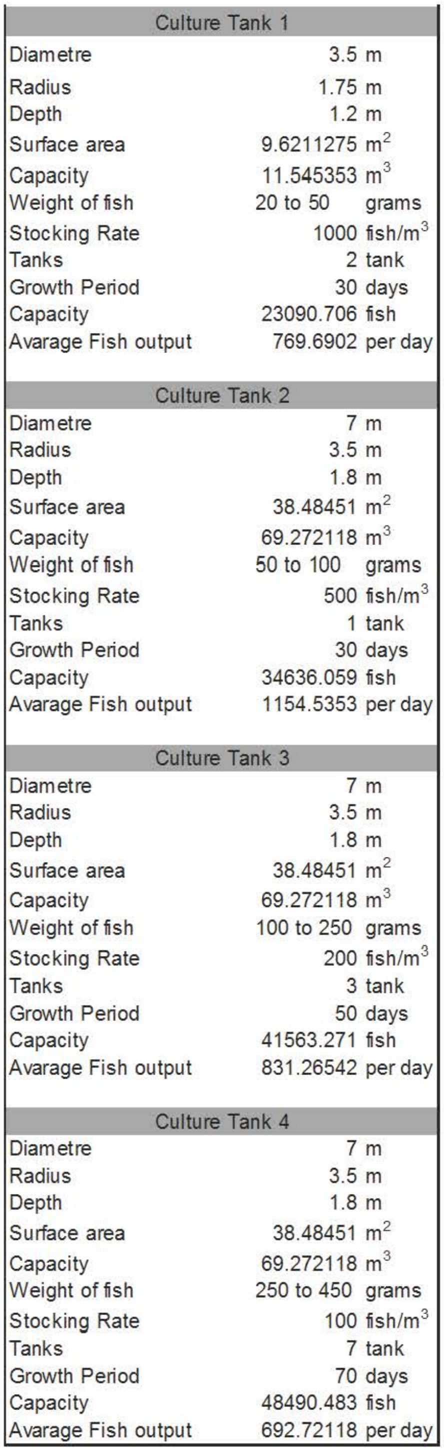


Table 8.3: Design parameters of the Aquaponic system



Aquaponic System		
Growout Tank (Fry)		
Parameter	Amount	Unit
Diametre	3.5	m
Radius	1.75	m
Depth	0.3	m
Surface area	9.6211275	m^2
Capacity	2.8863383	m^3
Weight of fish	0,02 to 1	grams
Stocking Rate	8000	fish/m^3
Tanks	1	tank
Growth Period	30	days
Fish Capacity	23090.706	fish
Avarage Fish output	769.6902	per day
Growout Tank (Fry)		
Diametre	3.5	m
Radius	1.75	m
Depth	0.7	m
Surface area	9.6211275	m^2
Capacity	6.7347893	m^3
Weight of fish	1 to 5	grams
Stocking Rate	3200	fish/m^3
Tanks	1	tank
Growth Period	30	days
Capacity	21551.326	fish
Avarage Fish output	718.37752	per day
Growout Tank (Fingelings)		
Diametre	3.5	m
Radius	1.75	m
Depth	1.4	m
Surface area	9.6211275	m^2
Capacity	13.469579	m^3
Weight of fish	5 to 20	grams
Stocking Rate	1600	fish/m^3
Tanks	1	tank
Growth Period	30	days
Capacity	21551.326	fish
Avarage Fish output	718.37752	per day



Culture Tank 1		
Diametre	3.5	m
Radius	1.75	m
Depth	1.2	m
Surface area	9.6211275	m^2
Capacity	11.545353	m^3
Weight of fish	20 to 50	grams
Stocking Rate	1000	fish/m^3
Tanks	2	tank
Growth Period	30	days
Capacity	23090.706	fish
Avarage Fish output	769.6902	per day

Culture Tank 2		
Diametre	7	m
Radius	3.5	m
Depth	1.8	m
Surface area	38.48451	m^2
Capacity	69.272118	m^3
Weight of fish	50 to 100	grams
Stocking Rate	500	fish/m^3
Tanks	1	tank
Growth Period	30	days
Capacity	34636.059	fish
Avarage Fish output	1154.5353	per day

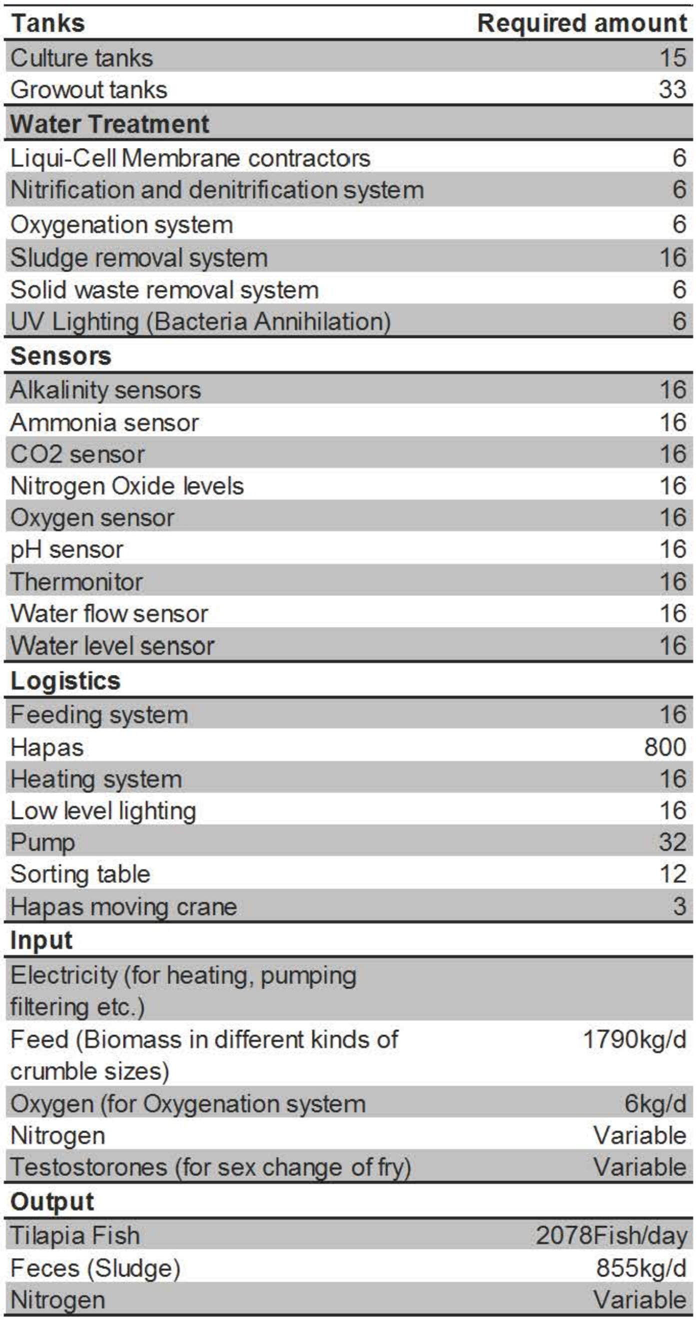
Culture Tank 3		
Diametre	7	m
Radius	3.5	m
Depth	1.8	m
Surface area	38.48451	m^2
Capacity	69.272118	m^3
Weight of fish	100 to 250	grams
Stocking Rate	200	fish/m^3
Tanks	3	tank
Growth Period	50	days
Capacity	41563.271	fish
Avarage Fish output	831.26542	per day

Culture Tank 4		
Diametre	7	m
Radius	3.5	m
Depth	1.8	m
Surface area	38.48451	m^2
Capacity	69.272118	m^3
Weight of fish	250 to 450	grams
Stocking Rate	100	fish/m^3
Tanks	7	tank
Growth Period	70	days
Capacity	48490.483	fish
Avarage Fish output	692.72118	per day

8.3 List of Equipments

The first initial list of equipments required for the aquaculture system are listed in the following Table:

Table 8.4: List of Equipments for aquacultural sub-system



Tanks	**Required amount**
Culture tanks	15
Growout tanks	33
Water Treatment	
Liqui-Cell Membrane contractors	6
Nitrification and denitrification system	6
Oxygenation system	6
Sludge removal system	16
Solid waste removal system	6
UV Lighting (Bacteria Annihilation)	6
Sensors	
Alkalinity sensors	16
Ammonia sensor	16
CO2 sensor	16
Nitrogen Oxide levels	16
Oxygen sensor	16
pH sensor	16
Thermonitor	16
Water flow sensor	16
Water level sensor	16
Logistics	
Feeding system	16
Hapas	800
Heating system	16
Low level lighting	16
Pump	32
Sorting table	12
Hapas moving crane	3
Input	
Electricity (for heating, pumping filtering etc.)	
Feed (Biomass in different kinds of crumble sizes)	1790kg/d
Oxygen (for Oxygenation system	6kg/d
Nitrogen	Variable
Testostorones (for sex change of fry)	Variable
Output	
Tilapia Fish	2078Fish/day
Feces (Sludge)	855kg/d
Nitrogen	Variable

Chapter 9

Lighting Domain

The debate between use of natural light against artificial lighting is foremost for designers dealing with the energy consumption question. Artificial lighting is chosen for the current design with the following factors influencing the choice:

- Vertical farms are typically designed for Polar Regions, deserts, mega-cities, where the availability of ambient light is limited or not conducive. For example, Polar Regions have long winters where the sunlight is unavailable, whereas in deserts the light intensity might be uncongenial for many plants.
- Plant growth does not depend on the full spectrum of sunlight. Plant growth can be optimized for a faster and a greater yield with artificial lighting.
- Unlike sunlight, artificial lights can be customized for plant growth. Customization may be based on the type of plant being cultivated, the stage of cultivation and the photo-period required by the plants, specific ranges of spectrum, luminous efficacy etc.

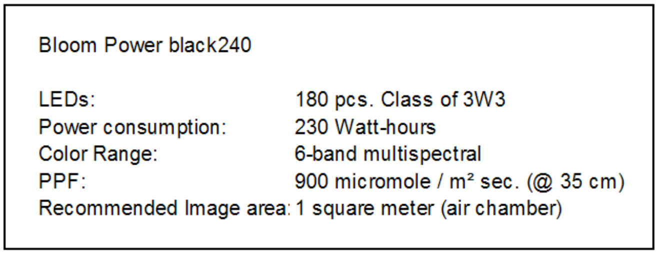
9.1 LED technology for lighting

LED (Light Emitting Diode) technology is chosen for the current VF design with its various advantages over other artificial lighting technologies. LED emit a low level of thermal radiation, have no hot electrodes, and have no high-voltage ballasts. LED also have a long operating life, which makes them a practical alternative for long-term usage involving plant production. One of the most appealing features of LED is that it is possible to modify the irradiation output to approximate the peak absorption zone of chlorophyll.

9.2 Baseline Design

The baseline design of the lighting system consists of several LED panels of the type Bloom Power black240$^{\text{TM}}$. One panel is shown in Figure 9.2.1 and has the following properties:

Table 9.1: LED Properties



Bloom Power black240	
LEDs:	180 pcs. Class of 3W3
Power consumption:	230 Watt-hours
Color Range:	6-band multispectral
PPF:	900 micromole / m^2 sec. (@ 35 cm)
Recommended Image area:	1 square meter (air chamber)

Consequently, one panel is required per square meter of growth area. The proposed VF design has a growth area of approximately 93000 m^2. Including a buffer, 95,000 LED panels are planned for the VF. Since a panel has about 180 LED, it amounts to a total of about 16.7 million LED (for 93,000 m^2). The LED on the panel provide different wavelengths leading to a spectrum suitable for plant growth. Figure 9.2.2 shows the spectrum of the panel compared to the response of different kinds of chlorophyll.

Figure 9.2.1: Color arrangement of the proposed LED panel

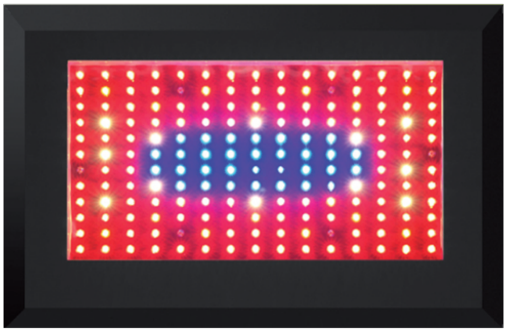
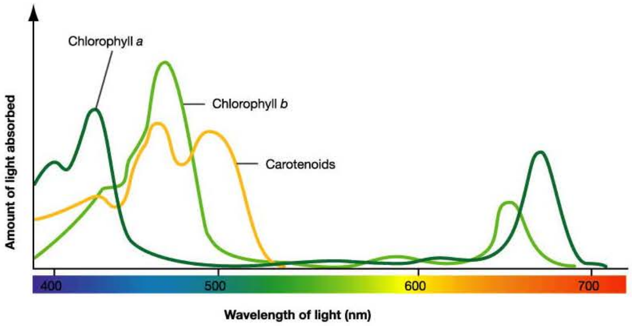


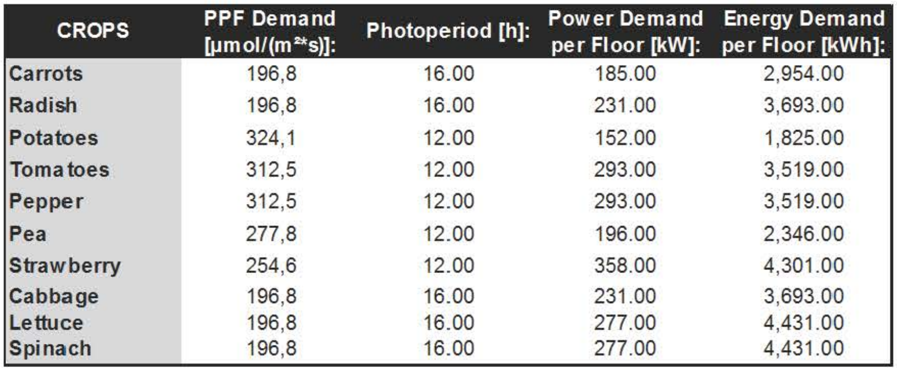
Figure 9.2.2: Response of chlorophyll compared to the spectrum of the LED panel



Source: [77]

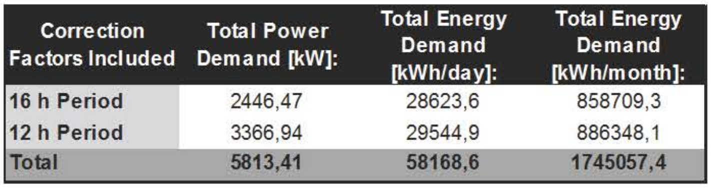
The selected plant species have different illumination requirements in terms of PPF (Photosynthetic Photon Flux). Therefore, the panels are not operated at maximum power. The panels will be operated on different power levels depending on the PPF requirements of the plant species. Furthermore, the desired duration of illumination is adapted to the needs of the plants, leading to 12 - 16 hours periods depending on the plant species (refer to Table 7.1). For the reduction of the power demand, the LED will be operated in a shutter sequence, which means that the LED are frequently turned on and off with a defined frequency. Investigations in plant response showed, that shuttering of LED do not affect the development and growing of plants, but can drastically reduce the required electrical energy. For the power calculations during this study a shutter factor of 0.9 is assumed [49], which means that out of a given photo-period the LED will remain off for 10% of the time. However, this will not be noticed by the plants since the frequency is kept high enough not to let the chlorophyll molecules reach ground state. Furthermore, younger plants need less illumination than adult ones. Consequently, the power demand of LED panels used for the illumination of young plants and seedlings is low. For the power estimations a plant development factor of 0.8125 is assumed [49]. This is because during initial phases a plant can not take light for the entire photo-period so taking all the phases into account only 80% (approximately) of the total energy needs to be spent for the entire growth cycle. Table 9.2 shows the power and energy demands per floor with respect to the different plant species, while Table 9.3 shows the total power and energy demand of the plant lighting system.

Table 9.2: Power and energy demand for the lighting system in the different growth floors



CROPS	PPF Demand [µmol/(m^2*s)]:	Photoperiod [h]:	Power Demand per Floor [kW]:	Energy Demand per Floor [kWh]:
Carrots	196,8	16.00	185.00	2,954.00
Radish	196,8	16.00	231.00	3,693.00
Potatoes	324,1	12.00	152.00	1,825.00
Tomatoes	312,5	12.00	293.00	3,519.00
Pepper	312,5	12.00	293.00	3,519.00
Pea	277,8	12.00	196.00	2,346.00
Strawberry	254,6	12.00	358.00	4,301.00
Cabbage	196,8	16.00	231.00	3,693.00
Lettuce	196,8	16.00	277.00	4,431.00
Spinach	196,8	16.00	277.00	4,431.00

Table 9.3: Total power and energy demand with correction factor



Correction Factors Included	Total Power Demand [kW]:	Total Energy Demand [kWh/day]:	Total Energy Demand [kWh/month]:
16 h Period	2446,47	28623,6	858709,3
12 h Period	3366,94	29544,9	886348,1
Total	**5813,41**	**58168,6**	**1745057,4**

Chapter 10

Fluid Delivery Domain

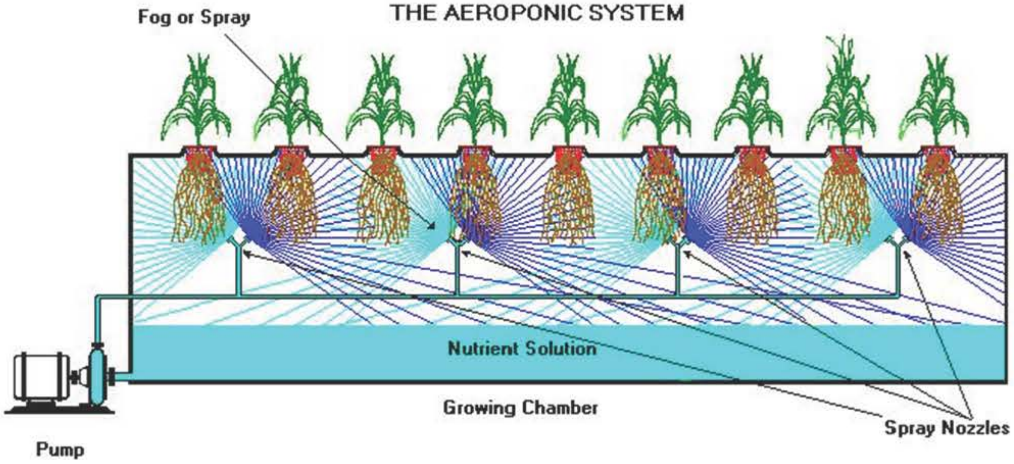
The fluid delivery system of this VF has special requirements not only because it must provide the water necessary for all the subsystems of the building and handle the sewage management as any normal industrial building, but also because it must provide the required nutrients for all the different crops as well as function as an irrigation system.

10.1 Requirements and Design Drivers

The entire system is based on the simple idea of having in the top of the building, a floor where the water and each nutrient are stored separately in different tanks by a powerful pump system located in the bottom of the building. Caused by the pressure of the fluids stored in those tanks, they can easily be distributed to the subsystems of each floor by a common piping system with no additional requirements. This storage floor is named NDS floor (Nutrient Delivery System floor). Apart from the growing floors, the rest of the floors require a standard fluid delivery system of any industrial building. Therefore, the subsystems of the growing floors are the only subsystem explained in depth in this chapter.

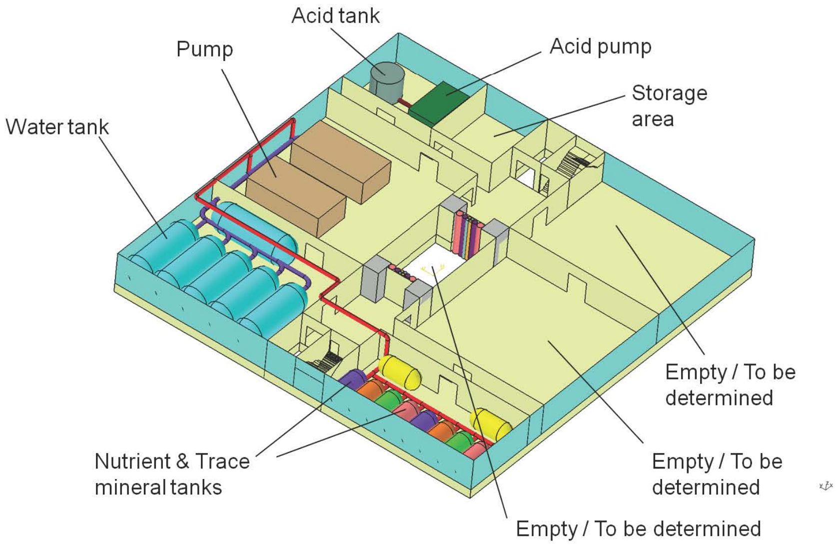
These subsystems are based on the aeroponic system, lately used by NASA for its Greenhouses bio-regenerative growth chambers. In short, it involves spraying a nutrient solution (exact solution of the nutrients required by the plant) directly to its roots which remain suspended in the air with no soil, as displayed in the following figure.

Figure 10.1.1: Standard aeroponic system



According to AgriHouse, Inc., growers choosing to employ the aeroponics method can reduce water usage by 90%, fertilizer usage by 60%, and pesticide usage by 100%, all while maximizing their crop yields by 45 to 75% [2]. By conserving water and eliminating harmful pesticides and fertilizers used in soil, growers are doing their part to protect the Earth. Moreover, the NASA Small Business Innovation Research (SBIR) results demonstrated that this aeroponic technology delivers an 80-85% increase in dry weight biomass per square meter, when compared to hydroponic and soil-based growing techniques. These results essentially proved that aeroponically grown plants absorb more nutrients compared to other growing techniques [50]. In order to optimize the produced crop in terms of quantity and quality, the nutrient solution must contain the exact composition of nutrient, sprayed in the optimal frequency, controlled by a computer. In addition, it must be also mentioned that not only each crop requires a different amount of its own optimum composition of nutrient solution, but also each growing phase of the crop will require a different one. Obviously, the optimal concentration is a matter of further research. However, this means that one aeroponic system will be required for every chamber in a floor (since it contains stacks with the same crop in the case phase), therefore, 8 aeroponic subsystems must be installed per floor.

Figure 10.1.2: Layout of NSD Floor

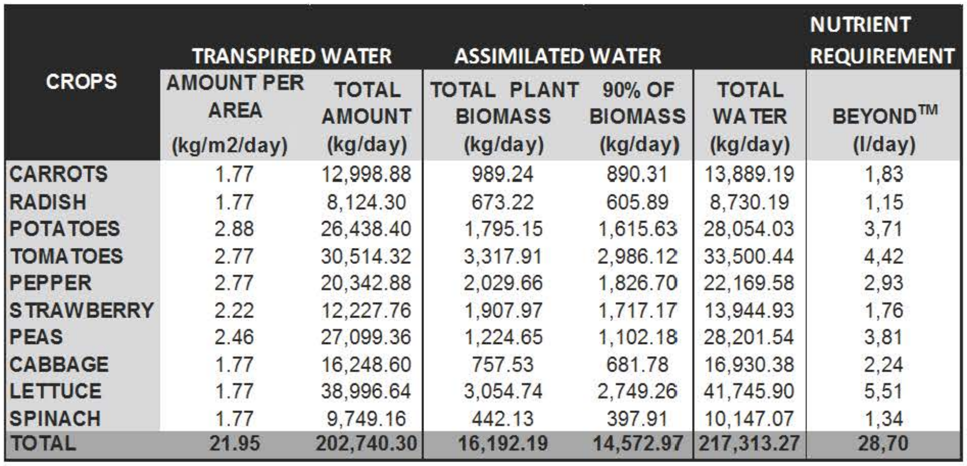


10.2 Consumption of water

The estimation is based on the fact that the plants uptake a certain amount of water in which one part becomes part of the biomass of the plant – an average of 90% of the crops biomass is only water – and the rest, which is the greatest part, is transpired out (refer to Table 10.1 for details). Consumption of water, approximately 217,000 l of water are required by the building per day out of which about 14,000 l is assimilated and leaves the tower in the form of produce and waste.

Obviously, the amount of water that is sprayed in each aeroponic subsystem is higher inasmuch as all the water will not reach the roots of the plants; nevertheless, this amount of water is directly recirculated to the water-recycling system to be processed and sprayed again, thereby closing the loop. In addition, with an appropriate water-recycling system as used in the Genesis series V Aeroponic system, the water usage and even the evaporation losses can be reduced down to minimal [1]. The exact water costs are difficult to measure as the possibilities are innumerable, from rain water harvesting to deep boring to urban grey water recycling. Therefore, this is kept open for research and inclusion of water costs into the cost analysis has been accounted to be null, although the estimations have been presented to help the reader fathom the volume of requirements.

Table 10.1: Water and nutrient requirement



CROPS	TRANSPIRED WATER		ASSIMILATED WATER			NUTRIENT REQUIREMENT
	AMOUNT PER AREA (kg/m2/day)	TOTAL AMOUNT (kg/day)	TOTAL PLANT BIOMASS (kg/day)	90% OF BIOMASS (kg/day)	TOTAL WATER (kg/day)	BEYOND^{TM} (l/day)
CARROTS	1.77	12,998.88	989.24	890.31	13,889.19	1,83
RADISH	1.77	8,124.30	673.22	605.89	8,730.19	1,15
POTATOES	2.88	26,438.40	1,795.15	1,615.63	28,054.03	3,71
TOMATOES	2.77	30,514.32	3,317.91	2,986.12	33,500.44	4,42
PEPPER	2.77	20,342.88	2,029.66	1,826.70	22,169.58	2,93
STRAWBERRY	2.22	12,227.76	1,907.97	1,717.17	13,944.93	1,76
PEAS	2.46	27,099.36	1,224.65	1,102.18	28,201.54	3,81
CABBAGE	1.77	16,248.60	757.53	681.78	16,930.38	2,24
LETTUCE	1.77	38,996.64	3,054.74	2,749.26	41,745.90	5,51
SPINACH	1.77	9,749.16	442.13	397.91	10,147.07	1,34
TOTAL	**21.95**	**202,740.30**	**16,192.19**	**14,572.97**	**217,313.27**	**28,70**

10.3 Fertilizer requirement

As already mentioned the idea is to mix the optimum fertilizer in each growing crop phase. This means that on the NSD floor, besides the water tanks, there must also be several nutrient tanks. The nutrients must be stored separately from each other in order to be delivered unmixed to the SMARTCONTROLLERs [3] (please refer to Table A.1). Plus, the waste management department might also produce several quantities of nutrients which can be used as fertilizer (please refer to the chapter on “Waste Management”).

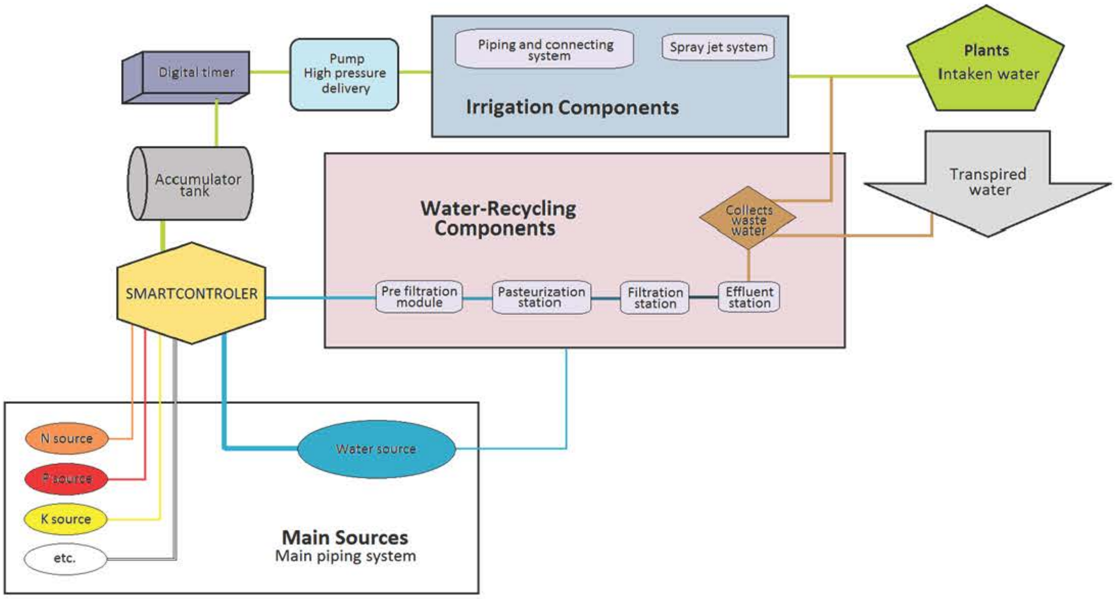
This complicates approximating the cost of fertilizer per day and is left for further research. Although, for the purpose of this study the cost for fertiliser is estimated assuming that 50% of the nutrient solution is purchased commercially and the rest is generated within the farm through composting.

The fertilizer used for this estimation is called BEYOND$^{\text{TM}}$, used by NASA for its aeroponic systems [50]. The state of the art shows that this is the most recommended fertilizer for this type of irrigation system. According to the application rates that the supplier [2] as well as NASA in its publications [50] recommend for aerospronic systems, the entire system needs approximately 30 litres of BEYOND^{TM} per day, leading to a cost of about 2000 € per day more details in Table 15.6 and A.1.

10.4 List of Equipments

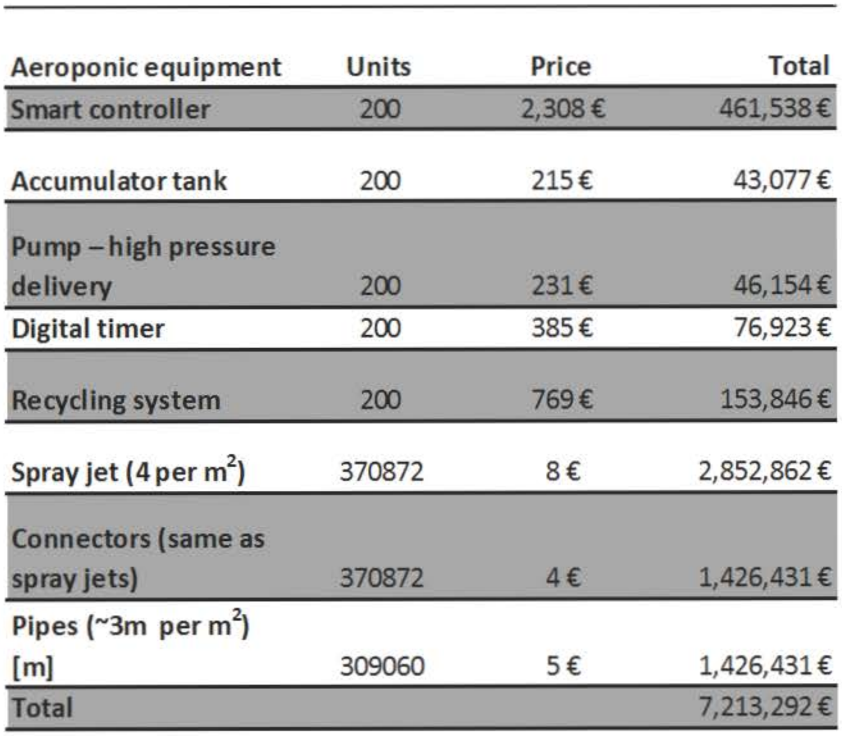
All the aeroponic subsystems have the same equipment which consists of two main circuits: the irrigation circuit which has the aim to provide the corresponding amount of optimum nutrient solution to the crop, and the water-recycling circuit which has the aim to collect and purify as much waste water as possible. The specific system is displayed in the Figure: 10.4.1 with all the required components.

Figure 10.4.1: Diagram of the aeroponic subsystem



As showed in the Table A.1, this aeroponic system based on the commercialized Genesis series V Aeroponic system 2 requires an estimated cost of 9.4 million of dollars – more details at Table 10.2. By adding this cost to the standard cost of a fluid delivery system for skyscrapers main pumping and piping systems and the several storage tanks in the NSD floor, the total necessary investment reaches approximately to 10 million of dollars for the entire system at most.

Table 10.2: List of equipments for the fluid delivery system



Aeroponic equipment	Units	Price	Total
Smart controller	200	2,308 €	461,538 €
Accumulator tank	200	215 €	43,077 €
Pump – high pressure delivery	200	231 €	46,154 €
Digital timer	200	385 €	76,923 €
Recycling system	200	769 €	153,846 €
Spray jet (4 per m^2)	370872	8 €	2,852,862 €
Connectors (same as spray jets)	370872	4 €	1,426,431 €
Pipes (~3m per m^2) [m]	309060	5 €	1,426,431 €
Total			7,213,292 €

Chapter 11

Environmental Regulation Domain

Aside from the structure, nutrient deliver system and lighting system, there is another system which is crucial for successful crop cultivation in the Vertical Farm; the environmental control system.

The environmental control system is required to maintain the desired air temperature and relative humidity for optimal plant growth. Additionally, the desired CO_2-levels need to be maintained in the plant cultivation floors to obtain maximum biomass yield, while still allowing safe conditions for the workers operating on the different floors. And as part of the air management, it is necessary to filter out contaminants and trace gases, such as ethylene, which are released into the air as by-products of the plant cultivation.

11.1 Baseline Design

Based on the tasks which need to be fulfilled by the environmental control system to maintain the desired air quality, it was possible to come up with a design for the environmental control floors. For the purposes of this design study, only the effects of the plant cultivation floors on the air quality of the Vertical Farm was taken into account. The influence of the fish farming floors, waste management floors, entrance floor, food processing floor, germination and cleaning floor and the fluid delivery floor are assumed to be minor compared to the plant cultivation floors.

In total, there are three environmental control floors, controlling the air quality of 8 or 9 plant cultivation floors. The design for the environmental control floor, shown in Figure 11.1.1a, is divided into four identical sections. Each section is linked to one of the four sections on the plant cultivation floors.

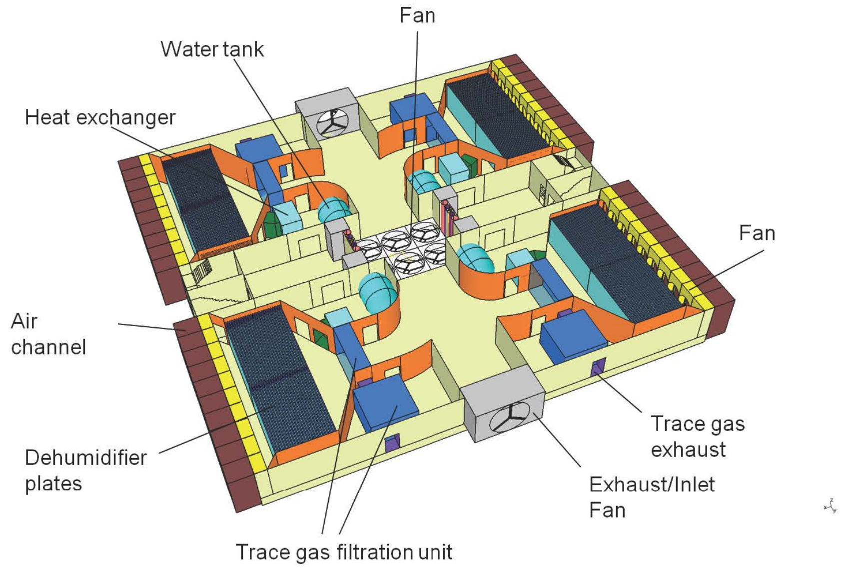
Warm, moist air comes from the different plant cultivation floors into the environmental control floor through the air channels and fans at the sides of the room. The air then passes through dehumidifier plates, which lower the temperature of the air and recover the water in the air through condensation. The condensed water is stored in buffer tanks, before being transported to the fluid delivery floor. After the warm, moist air has passed the dehumidifier plates, it enters the trace gas filtration unit as cooler, drier air. In the trace gas filtration unit, contaminants and trace gases are removed from the air through filters, before exiting the building through (trace gas) exhausts.

The purified air exiting the trace gas filtration unit is guided into the centre of the floor, where it enters the large air channel which leads back down to the plant cultivation floors. Carbon dioxide levels desired for optimal plant growth are obtained through injection of CO_2 at the plant cultivation floors. The required CO_2 is pumped up through piping from the carbon dioxide tanks in the waste management floor. Using data from [48] and the calculated grow area for the different crops it was possible to calculate the amount of CO_2 absorbed by the plants each day. The results can be found in Table 11.1. At sea level conditions, 2379.83 kilograms of carbon dioxide gas corresponds to about 1270 m^3. When necessary, two large fans at the sides of the room can be used to force old air out of the building, or to let new air into the building.

The heat which is removed from the air by a heat exchanger, when it passes through the dehumidifier plates, is transported to the roof, where it is released to the outside air via large heat dissipation units, see Figure 11.1.1b. The roof also holds the pumps and cooling fluid tanks which are required for the various heat exchangers in the building to work.

Figure 11.1.1: Layout of the Environmental Control Floor

(a) Intermittent floors



(b) Roof

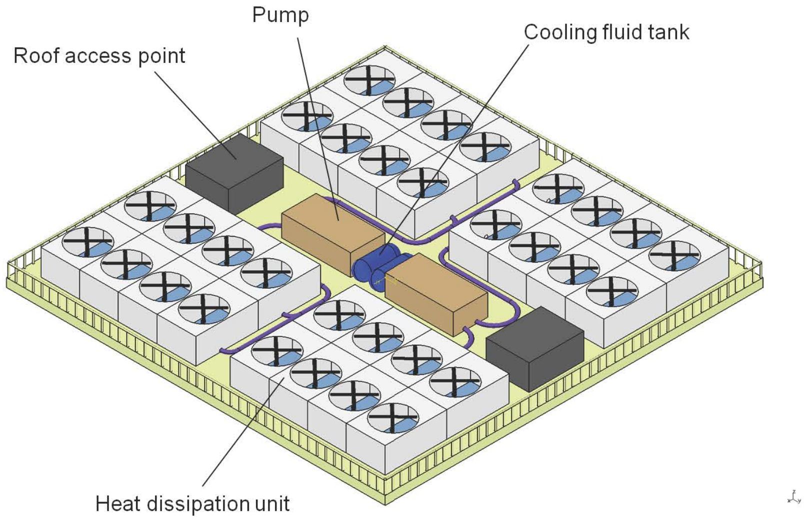
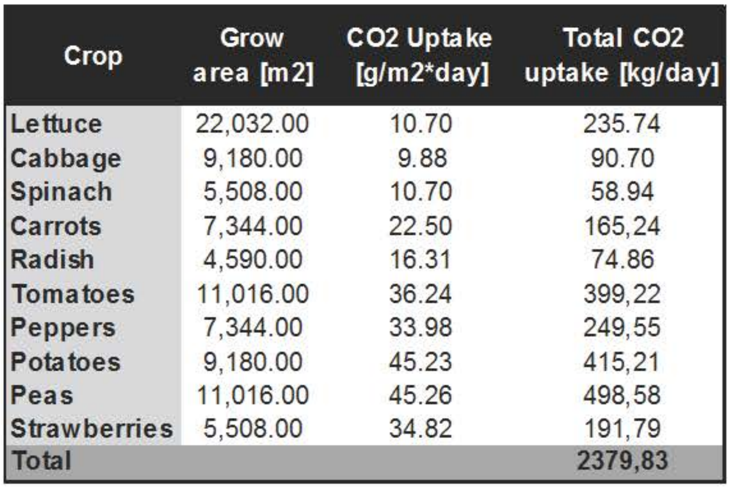


Table 11.1: Carbon dioxide uptake per day



Crop	Grow area [m2]	CO2 Uptake [g/m2*day]	Total CO2 uptake [kg/day]
Lettuce	22,032.00	10.70	235.74
Cabbage	9,180.00	9.88	90.70
Spinach	5,508.00	10.70	58.94
Carrots	7,344.00	22.50	165,24
Radish	4,590.00	16.31	74.86
Tomatoes	11,016.00	36.24	399,22
Peppers	7,344.00	33.98	249,55
Potatoes	9,180.00	45.23	415,21
Peas	11,016.00	45.26	498,58
Strawberries	5,508.00	34.82	191,79
Total			2379,83

11.2 HVAC calculations

The engineering discipline dealing with the management and control of air quality inside a building is a complex one. For an accurate design of the Heating, Ventilation and Air-Conditioning (HVAC) system, precise data for the various heat sources, air flows and leakage rates, among other parameters, need to be determined for the Vertical Farm. Furthermore, the external conditions of the air around the Vertical Farm can have a high impact on the design and performance of the HVAC system, making it highly dependent on the location of the Vertical Farm.

For this study into the economic feasibility of the Vertical Farm, only rough estimates and preliminary calculations will be performed for the HVAC system.

11.2.1 Desired Conditions and Assumptions

It is assumed that the temperature of the air in the Vertical Farm should be kept at 25 °C, and the desired relative humidity (RH) of the air is 70%. While these values are likely to differ slightly for each crop type, it is deemed suitable for the first analysis of the HVAC system. Another assumption which is made is that the transpiration of water by plants occurs at the same rate regardless of the relative humidity, until the air reaches 100% RH.

For the determination of the available grow area per crop per floor, it was necessary to calculate the maximum number of stacks. For this calculation it was assumed that there was at minimum, 10 cm between the plant canopy and the illumination system. For the air flow calculations in the next section, it is assumed that the air flow below the plant canopy is negligible.

As calculated, there are 95,000 LED panels in the Vertical Farm, consuming a peak power of 5,929.68 kW and a total energy per day of 59,331.97 kWh. For the calculations in this chapter, the peak power will be used to determine the amount of cooling required.

It is assumed that 70% of the power used by the LEDs is transformed into heat, which needs to be dissipated with cooling liquid, through heat exchangers and finally transferred to the heat dissipation units on the roof. It is assumed that the heat transfer from the LEDs to the air is negligible.

As mentioned before, only the influence of the plant cultivation floors is considered. Furthermore, the power consumption of the HVAC system itself is not yet taken into account.

11.2.2 Flow Rate

Psychrometrics is a discipline dealing with the determination of physical and thermodynamic properties of gas-vapour mixtures. For a specific constant pressure, the thermodynamic properties of a gas-vapour mixture can be determined and presented graphically in a psychrometric chart [9].

Figure 11.2.1 shows such a psychrometric chart for air at sea level elevation [88]. On the horizontal axis it gives the dry bulb temperature, as determined by an ordinary thermostat, while the vertical axis indicates the humidity ratio, which indicates the mass of water per unit mass of dry air.

Other parameters which can be determined from the graph are the wet bulb temperature, dew point, relative humidity, specific volume and specific enthalpy. For a given pressure, if any two parameters are known, it is possible to determine the other parameters by using a psychrometric chart.

The desired dry bulb temperature is taken to be 25 °C, with a RH of 70%, as mentioned earlier. According to Figure 11.2.1, at 25 °C and 70% RH, the humidity ratio is 0.0138 g of water per gram of dry air. At the same temperature, but at 100% RH, the humidity ratio is about 0.020 g of water per gram of dry air.

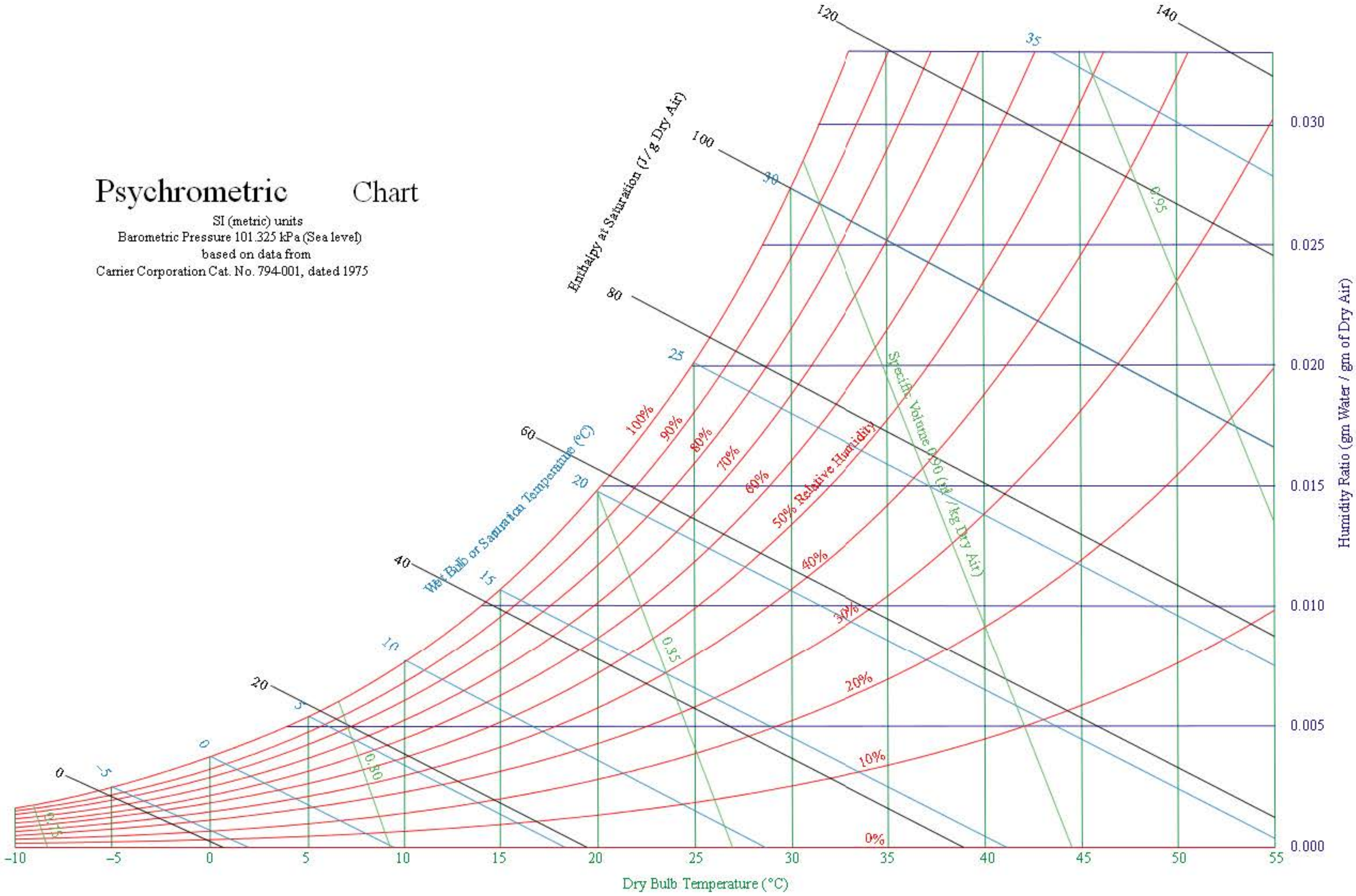
Thus, a maximum of 0.0062 g of water can be absorbed per gram of dry air, when the temperature is kept constant. At 25 °C, the density of air at sea level pressure is 1.1839 kg/m^3, which means that 1 gram of dry air occupies $8.45\times10^{-4}m^3$ and hence, the maximum amount of water which can be absorbed per cubic meter of air is 7.34018 g.

Furthermore, it can be determined that the maximum amount of water transpired into the air per m^2 is 2.88 kg/day, which corresponds to 0.0333 $g/m^2/s$. A maximum grow area of 5508 m^2 per floor was calculated. The total amount of air volume per floor is roughly 5600 m^3 (floor is 40 by 40 by 3.5 m). This means that 1 m^2 of grow area corresponds to 0.98 m^3 of air and thus the maximum transpiration rate is 0.034 $g/m^2/s$.

With this transpiration rate it would take about 215 seconds for the air to become saturated with water. This means the air over the plant canopy needs to be refreshed once every 215 seconds, or roughly once per 3.58 minutes.

For design purposes, a 100% margin is included, leading to a refresh rate of 0.56 times per minute. For the total Vertical Farm, there is 92718 m^2 of plant cultivation area, which corresponds to an air volume of 90,863.64 m^3. A refresh rate of 0.56 times per minute for this total volume results in a flow rate of 50883.64 $m^3/minute$, or 848.06 m^3/s, for the entire Vertical Farm. The three environmental control floors each need to handle about a third of this, meaning 282.69 m^3/s.

Figure 11.2.1: A psychrometric chart for sea-level elevation



Source: [54]

11.2.3 Heating and Cooling

Air: The dehumidifier plates work by condensation of the water vapour in the air. This is achieved by reducing the temperature, until the saturation point is reached. Then, when the air is cooled further, the water in the air will be forced to condense. Here it is assumed that the air coming into the dehumidifier plates is at 25 °C dry bulb temperature, with 100% RH. By using the psychrometric chart shown in Figure 3, it is possible to determine the amount of cooling which is required to reduce the humidity to the right amount.

As observed earlier, the humidity ratio at 70% RH and 25 °C dry bulb temperature is 0.0138 g of water per gram of dry air. Thus, the dehumidifiers should cool the air to precisely that dry bulb temperature where the humidity ratio is 0.0138 at 100% RH. To determine this temperature, draw an imaginary horizontal line from the intersection between the 70% RH curve and the 25 °C dry bulb temperature line towards the left. At the intersection between this imaginary line and the 100% RH curve, draw a vertical line downwards. The intersection of this vertical line with the horizontal axis allows for determination of the desired, cooled air, temperature, which for this case is roughly 17.5 °C.

Cooling the air from 25 degrees to 17.5 °C, means a reduction in enthalpy of the air from about 76.4 J/g to 52.7 J/g. Combine this with a flow rate of $282.69 m^3/s$, and a density of 1.1839 kg/m^3 gives a total amount of energy removed from the air equal to: 7.93 MJ/s per floor. Part of this energy can be used to re-heat the air to the desired 25 °C. This would require an increase in enthalpy from 52.7 J/g to about 60.3 J/g, which corresponds to: 2.54 MJ/s per floor. Thus in total, 5.39 MJ/s of heat needs to be removed from the air on each environmental control floor and 16.2 MJ/s from the entire Vertical Farm.

LED: Aside from the temperature and humidity control of the air, it is also necessary to cool the LED panels, to prevent them from breaking down or transferring excess heat to the air. The assumption was made that the transfer of heat from the LEDs is negligible, even though 70% of the power used by the lighting system is transformed into heat.

To ensure that the design has some margin, the cooling system for the LEDs will be sized based on the peak power used by the lighting panels, which is 5,929.68 kW. The total amount of heat produced is 70% of this value, so about 4.2 MJ/s.

11.2.4 Environmental Control System Sizing

Fans: Each environmental control floor needs to handle an air volume flow of 282.69 m^3/s. To achieve this, there are six large fans in the centre of each environmental control floor, which force the air down towards the plant cultivation floors. The fan type which was selected is the RDA 1000 by Nicotra Gebhardt [52].

Based on the diagram, the RDA 1000 would use roughly 115 kW (without losses) to handle 50 m^3/s. The air velocity would be around 31 m/s and the fan rotation speed around 1750 rpm. The total pressure would be 750 N/m^2, with a dynamic pressure of 600 N/m^2. It should be noted that this fan selection is just to get an indication of the power consumption and the fan performance. The noise level produced by these fans, when operating at the above mentioned conditions, would be higher than 110 dB and hence unacceptable. No calculations have been performed to determine the exact required dynamic pressures of the system, but it is envisioned that two small fans will be placed in each of the ducts leading from the plant cultivation floors to the environmental control floors. The flow through these ducts has a flow rate of at most 8.84 m^3/s. The fan selected for placement in the ducts is the RDA-E 560 [52]. For a volume of 9 m^3/s, the fans would use a minimum of 7.8 kW (without losses), while increasing the dynamic pressure by about 187 N/m^2. There are four ducts per plant cultivation floor, meaning eight fans per plant cultivation floor, for a total of two-hundred of these ‘small’ fans.

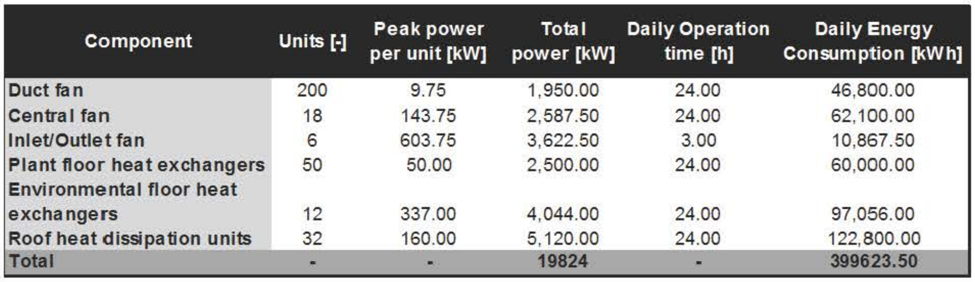
For the inlet/outlet fans at the sides of the environmental control floors, it is assumed that these will need to be custom designed to handle half of the volume of 282.69 m^3/s, so 141.35 m^3/s. For the expected power consumption of one of these fans, the combined power consumption of three of the fans in the centre of the environmental floor is taken, and this is multiplied by a factor of 1.4 to obtain a power consumption of 483 kW, not yet taking into account any losses. It is assumed that the actual fans which will be used in the building will be able to provide the performance of the above mentioned fans, but that they will do so at an efficiency of 80%. Taking into account the efficiency, and the number of fans, it is possible to estimate the power and energy consumption of the fans. This can be found in Table 11.2.

Heat exchangers: The maximum plant cultivation area for a single floor is 5508 m^2. This means that the maximum number of LED panels for a single floor is 5508. Since 95,000 LED panels require a peak power of 5929.68 kW, the power required by 5508 panels would be about 311.06 kW. Per plant cultivation floor there are two heat exchangers, which will be sized to handle 200 kWTh of cooling. Two heat exchangers per plant cultivation floor gives 50 in total. Additionally, there are heat exchangers on the environmental control floors, which are used for temperature control of the air. There are four heat exchangers on each of the environmental control floors, which have to remove 5.39 MWTh of heat from the air. Thus, each of the heat exchangers needs to remove 1.348 MWTh. The amount of power consumed to remove this heat can be determined using one of three interchangeable parameters: The coefficient of performance (COP), the energy efficiency ratio (EER) and the seasonal energy efficiency ratio (SEER). Each of these parameters indicates the ratio of output cooling to input electrical power. The COP is a unit-less parameter, while EER and SEER are given in $Btu/W/hr$. SEER differs from the other two parameters in that it represents the overall performance over a certain range of operating conditions, rather than the performance for one specific condition.

A new residential air conditioning systems in America require a SEER rating of at least 13, [89] which corresponds to a COP of about 3.3. There are systems being produced already which have SEER ratings higher than 20, or COP values of higher than 4.2 [34, 53]. The heat exchangers for the Vertical Farm are likely to be custom designed to handle the large volume flows and large cooling loads with high efficiency. Therefore, a reasonably high value for the COP of 4 is taken for the heat exchangers. This means that the required electrical power is

4 times lower than the cooling load of the heat exchangers. Thus, the heat exchangers on the plant cultivation floors will require 50 kW of power, while the heat exchangers on the environmental control floors will use 337 kW. The heat dissipation units on the roof need to dissipate all the heat from the air and the LEDs, which amounts to 20.4 MW. There are 32 heat dissipation units, so each needs to handle 637.5 kW. Assuming again a COP of 4, this means that each unit consumes about 160 kW. The power and energy consumption of the heat exchangers can be found in Table 11.2.

Table 11.2: Power and Energy consumption of the Environmental Control Floors

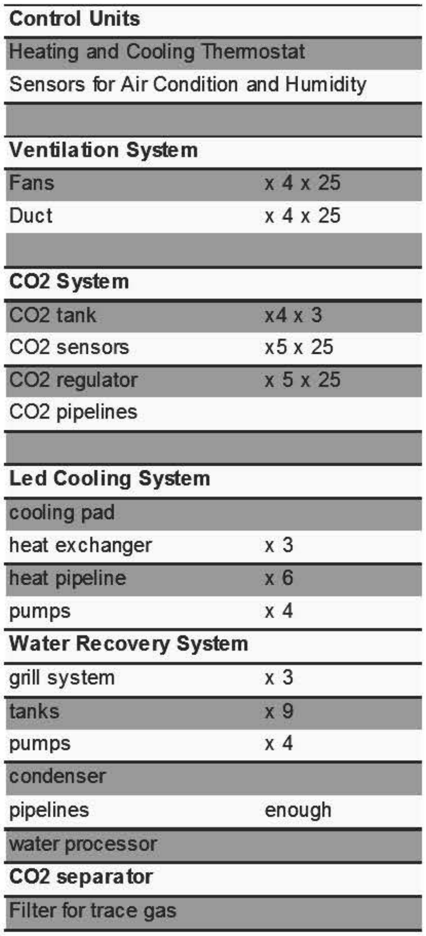


Component	Units [-]	Peak power per unit [kW]	Total power [kW]	Daily Operation time [h]	Daily Energy Consumption [kWh]
Duct fan	200	9.75	1,950.00	24.00	46,800.00
Central fan	18	143.75	2,587.50	24.00	62,100.00
Inlet/Outlet fan	6	603.75	3,622.50	3.00	10,867.50
Plant floor heat exchangers	50	50.00	2,500.00	24.00	60,000.00
Environmental floor heat exchangers	12	337.00	4,044.00	24.00	97,056.00
Roof heat dissipation units	32	160.00	5,120.00	24.00	122,800.00
Total	**-**	**-**	**19824**	**-**	**399623.50**

11.3 List of Equipments

For the environmental control system the required equipment are as follows.

Table 11.3: List of equipments for environmental control



Control Units	
Heating and Cooling Thermostat	
Sensors for Air Condition and Humidity	
Ventilation System	
Fans	x 4 x 25
Duct	x 4 x 25
CO2 System	
CO2 tank	x4 x 3
CO2 sensors	x5 x 25
CO2 regulator	x 5 x 25
CO2 pipelines	
Led Cooling System	
cooling pad	
heat exchanger	x 3
heat pipeline	x 6
pumps	x 4
Water Recovery System	
grill system	x 3
tanks	x 9
pumps	x 4
condenser	
pipelines	enough
water processor	
CO2 separator	
Filter for trace gas	

Chapter 12

Food Processing Sub-system

When plants and fish are full-grown they need to be harvested and readied for delivery to supermarkets and restaurants. This is done on the food processing floor. On the food processing floor plants and fish are processed by workers or by the food processing machinery into consumables. Food processing takes harvested crops and fish and uses these to produce direct-to-market products with long shelf-life. For example, the planned supermarket can be directly supported by the produces of the tower, in addition a restaurant could also be conceived in conjunction, following the models of Whole Foods^{TM}, Ikea^{TM}or Karstadt^{TM}.

12.1 Requirements and Design Drivers

The requirements for a food processing floor are listed below:

- Buffer storage unit
- Cutting and working units
- Conveyors
- Cleaning units
- Packaging units

- Storage units for finished products
- Observation room, break room and offices

12.2 Baseline Design

The food processing floor is divided into the food section, at the left part of the floor, the fish section, the observation room, the break room and offices, at the right part of the floor (see Figure 12.2.1). In the corridor of the food processing floor, buffer, water and power supply systems are placed. The harvested food has to be temporary stored before processing further. This step keeps food in the shade, without any possible contact with sunlight and also protects these from possible attack (by rodents, insects, etc.). In the sorting process; damaged and foreign bodies are removed from the food. The non-edible biomass can be dumped here and it will fall down the chute to the waste management floor. In addition, there are place-holders for work areas, such as cutting surfaces, but also a washing machine that wash harvested food to remove micro-organisms or chemical residues. The three machines in the food section indicate packaging machines for different kind of food. The packaging sector consists of conveyors for sorting the food, because it is likely that the food processing floor has to deal with a large variety of produce, so different packaging methods will be used for different products. A stock is also placed there to store the material for packaging, such as cups, Styrofoam, etc. Additionally, the food processing floor consists of working areas, such as offices, a break room for the workers and an observation room to control the units of the VF building.

The fish processing section consists of place-holders for work areas, such as cutting, sorting, checking the freshness status, etc. Controlling is needed in order to identify that the fish is suitable for further processes. In the next step, the fish is processed by a fish cleaning machine, operated by a single person. The cleaning machine uses high-pressured water jets, which are capable of eviscerating and individually scaling the fishes. After the cleaning process, the fish will be sent to the machine for packaging. A stock is also placed in this section to supply material for packaging. Packaged fish can be stored in the cold room.

Figure 12.2.1: Layout of the food processing floor

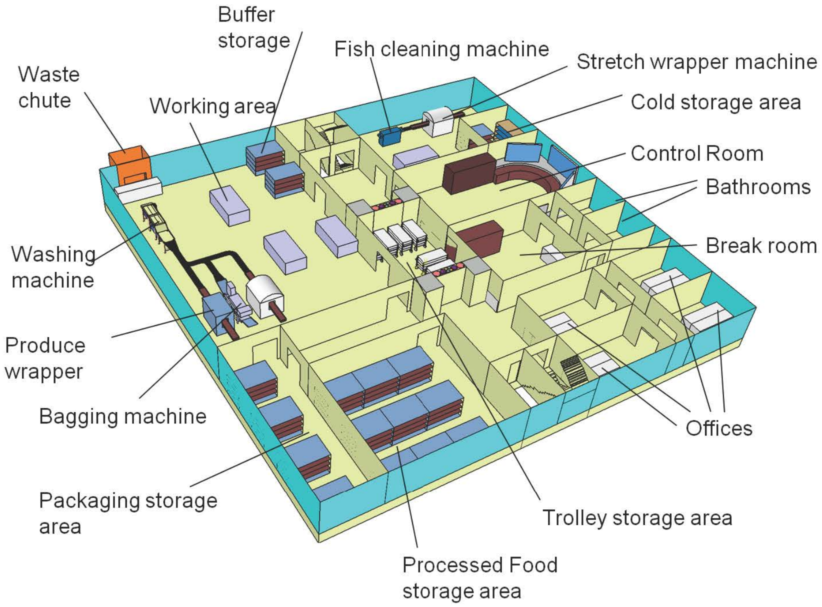
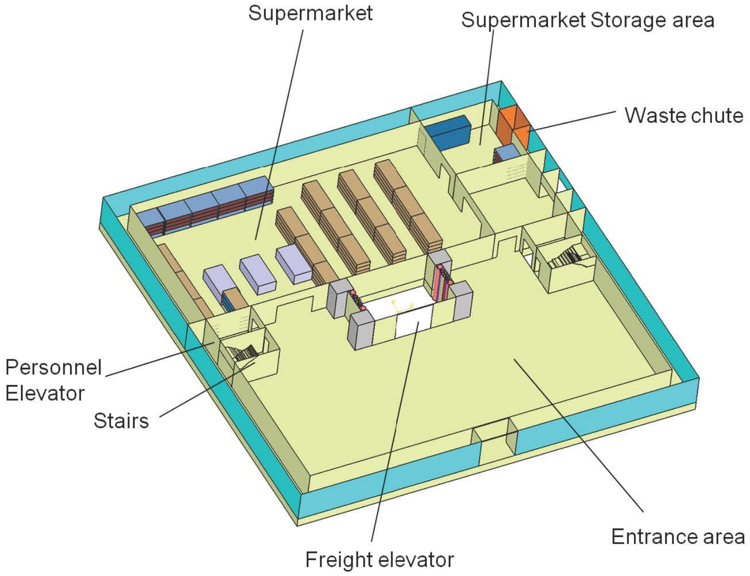


Figure 12.2.2: Layout of Supermarket/Delivery Area



12.3 List of Equipments

A tentative list of equipments required for food processing and packaging is as follows:

Table 12.1: List of equipments for food processing

(a) List of equipments for post harvest

Machine	Function	Price	Performance	Kilowatt
Polywash™ Multi-Produce Washers	Washing	45.000,00 €	up to 50 tons per hour	8
Roll Stock Poly Bagger	Packaging	30.000,00 €	approx. 2000 bags per roll	3
Stretch Wapper	Packaging	35.000,00 €	up to 30 trays per minute	2,5
Produce Wapper	Packaging	35.000,00 €	up to 30 packages per minute	3
Conveyors	Transportation	30.000,00 €	Throughput: 120 - 180 t per hour; 1.3 - 2.0 m/s	5
Computer	Controlling	4.000,00 €	-	5

(b) List of equipment for fish processing

Machine	Function	Price	Performance	Kilowatt
Fish Speed cleaning machine	Washing & Cleaning	15.000,00 €	about 30 fish per minute	3,5
Stretch Wapper	Packaging	35.000,00 €	up to 30 trays per minute	2,5
Conveyors	Transportation	3.000,00 €	Throughput: 120 - 180 t per hour; 1.3 - 2.0 m/s	5
Computer	Controlling	1.000,00 €	-	5

Figure 12.3.1: Polywash™ Multi-Produce Washers washing machine (left), Stretch Wrapper packaging machine (right)

Chapter 13

Waste Management Sub-system

Aside from producing edible biomass, the Vertical Farm also generates bio-waste (e.g. leaves, stems, fibrous roots, damaged fruit and vegetables) as a by-product of crop cultivation, as well as fish waste from the fish farms.

The annual waste produced by the plant growth floors of the Vertical Farm was calculated to be roughly 2443 metric tons. The waste produced by the fish farms was determined to be about 517 tons. Since it was assumed that 1 ton of plant waste is used as fish feed each day, the remaining waste is roughly 7.11 tons per day on average.

To close the functional loop of the Vertical Farm, this waste should be converted into useful resources, such as liquid fertilizer of bio-fuel. The design for the Vertical Farm incorporates two Waste Management floors which do exactly that.

13.1 Baseline Design

The Waste Management floors can be used for bio-gas production and nutrient recovery from waste. For the purposes of this design study, only the bio-gas production through Anaerobic Digestion (AD) is calculated.

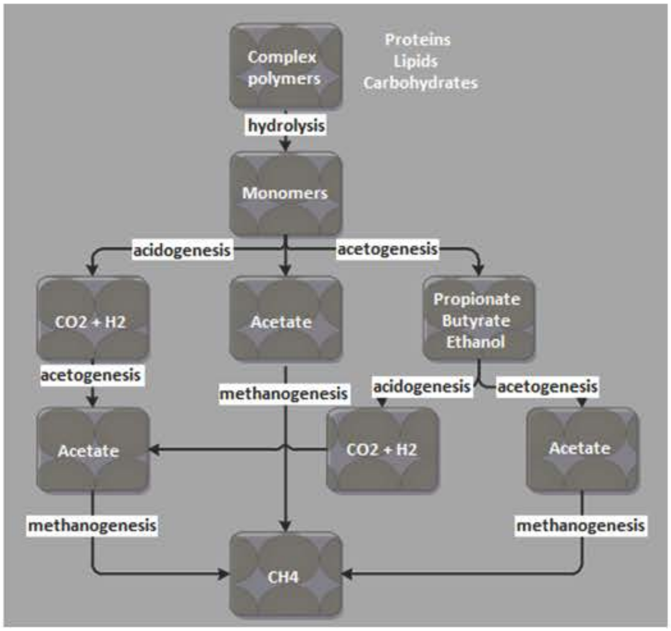
A brief description of the AD and nutrient extraction processes is given below, after which the designs for the Waste Management Floors are presented and discussed.

13.1.1 Anaerobic Digestion

Anaerobic Digestion, see Figure 13.1.1, is a mature technology to produce bio-gas from solid waste [46]. The AD process breaks down the organic content (e.g. cellulose, lignin) in the waste into bio-gas with the help of microbial activity. The process uses a variety of bacteria and microbes to break down the complex organic molecules into bio-gas.

As can be seen in Figure 13.1.1, the AD process occurs in four stages: Hydrolysis, followed by Acidogenesis, Acetogenesis and finally Methanogenesis.

Figure 13.1.1: Anaerobic Digestion process diagram



Source: [29]

Hydrolysis is a (chemical) process in which water is added to a substance to break chemical bonds, splitting the substance into multiple, less complex, parts. In the AD process, hydrolysis facilitates the breakdown of complex molecules into sugars, fatty acid and amino acids under controlled values of pH and with specific retention times. Depending on the composition of the bio-waste, the hydrolysis process determines the eventual hydrogen potential of the bio-gas end-product [46].

The acidogenesis phase of the AD process generates carbonic acids, alcohols, carbon dioxide and hydrogen from the simple monomers being formed through hydrolysis. Acetogenesis, the third phase of the anaerobic digestion, uses bacterial species known as acetogens to produce acetate from carbon (e.g. CO_2) and energy sources (e.g. H_2).

Methanogenesis, also known as bio-methanation, is the final step of the anaerobic digestion process. Methanogens, micro-organisms from the Achaean domain, produce methane as a metabolic by-product. When acetate is given as input, methane and carbon dioxide are produced. Methanogenesis has been shown to occur with other sources of carbon, such as carbon dioxide and formic acid, which use different reactions to form methane and as such can also result in other by-products.

The specific bio-gas yield of an anaerobic digester depends on a variety of factors. First and foremost is the composition of the bio-waste which is fed into the digester. “The diversity of organic solid waste, regarding origin, composition and production period, calls for the specific investigation of each kind of waste when digested alone and in combination with others” [56]. Depending on the type of waste which is to be processed, a trade-off should be made on the technological and economic feasibility of the reactor process for the different digester types. For this trade-off it is also important to take into account the Organic Loading Rate (OLR), which is a measure of the amount of waste fed into the reactor per day. For a stable digestion process, the OLR should be below some maximum value, which is specific to the AD reactor. Somewhat related to the Organic Loading Rate is the Hydraulic Retention Time (HRT) which is a measure of the duration of the AD process. In general a lower OLR means a higher HRT, which leads to a higher bio-gas/methane yield.

Of course, not all of the bio-waste which is fed into the anaerobic digesters is transformed into methane, or other by-products. Instead, a residue of substrate, known as digestate, will remain after the bio-gas generation process is complete. This residue, a mixture of organic waste, contains carbon and nitrogen (among other elements), making it potentially suitable as a fertilizer. The amount of finished digestate, meaning digestate which has been processed to remove unwanted (harmful) components such as hydrogen sulphide, which is produced by an AD reactor can range from 20 to 40% of the total waste material delivered to the digester [87].

13.1.2 Nutrient extraction process

The nutrient extraction process is based on pumping a shredded bio-waste and water mixture, or digestate from the AD process, into (fermentation) tubes filled with volcanic rock particles. The volcanic (lava) rock particles act as filter media/biomass carrier media. The lava rock particles along with a combination of aerobic and anaerobic biological processes, allow for extraction of nutrients (e.g. nitrogen, phosphorus) and removal of suspended solids without the use of chemicals. Thus, the output of the process is nutrients, (non-potable) water and some left-over waste.

13.1.3 Waste Management Floor design

Figure 13.1.2 shows the layout for the first Waste Management Floor. Waste enters the Waste Management Floor through a waste chute, which connects directly to the Food Processing Floor. This waste falls onto a conveyor belt and is led through a shredder machine, before exiting into a large storage container. From this large storage container, smaller waste containers (max 1 ton) are filled. These smaller waste containers are then moved around using forklift trucks to either the bio-gas domes, or the mixing tank. As mentioned previously, the bio-gas domes, with connected buffer tanks, are used to convert bio-waste into bio-gas. Each bio-gas dome has a reserved space which is left open to allow easy movement of a forklift truck, which is used to transport up to 1 ton of waste at a time. The mixing tank is used to mix the shredded waste with water, before it is pumped into special fermentation tubes for the nutrient extraction process. The resulting nutrient solution is fed into a fluid separator, to obtain water and highly concentrated nutrient solution. The water used in the mixing tank and the bio-gas domes, comes from two large water buffer tanks.

Aside from these components, a large freight elevator shaft is placed in the middle of the room, which allows for movement of the forklift truck(s) between the Waste Management Floors and the Entrance floor. Additionally there are elevators for personnel to move between the floors of the Vertical Farm, as well as (emergency) staircases. The second Waste Management Floor, see Figure 13.1.3, also has bio-gas domes, like the first floor. The remaining part of the floor is used for gas storage and power generation. Gas from the bio-gas domes is led into a gas separation unit, with two gas separation membranes. Here, the bio-gas is split into carbon dioxide gas and methane gas. Both the CO_2 and CH_4 gas are then led into (separate) compressors, which force the gas into tanks. The CO_2 tanks are used for crop cultivation, while the methane tanks are connected to turbines for power generation. Some Power Control Units are also present to control the turbine operation.

Figure 13.1.2: Plan of Floor 1

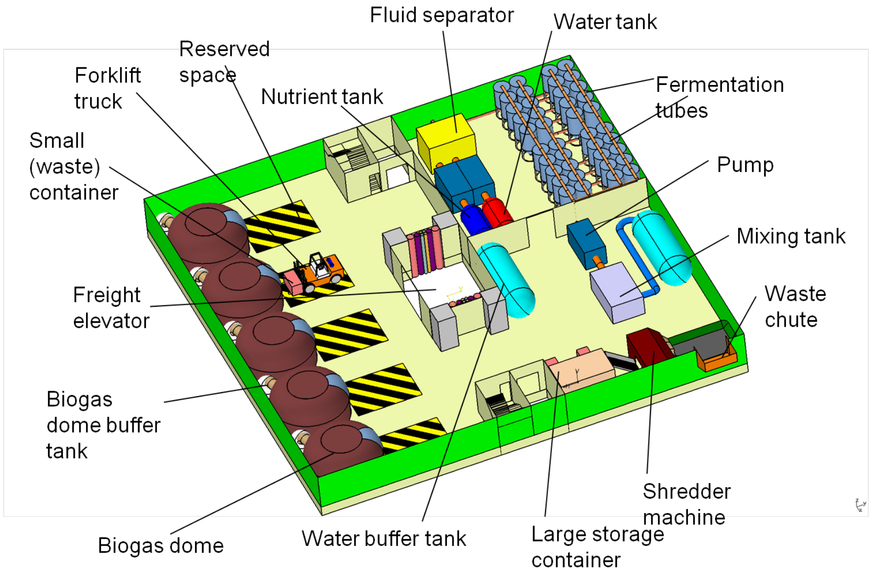
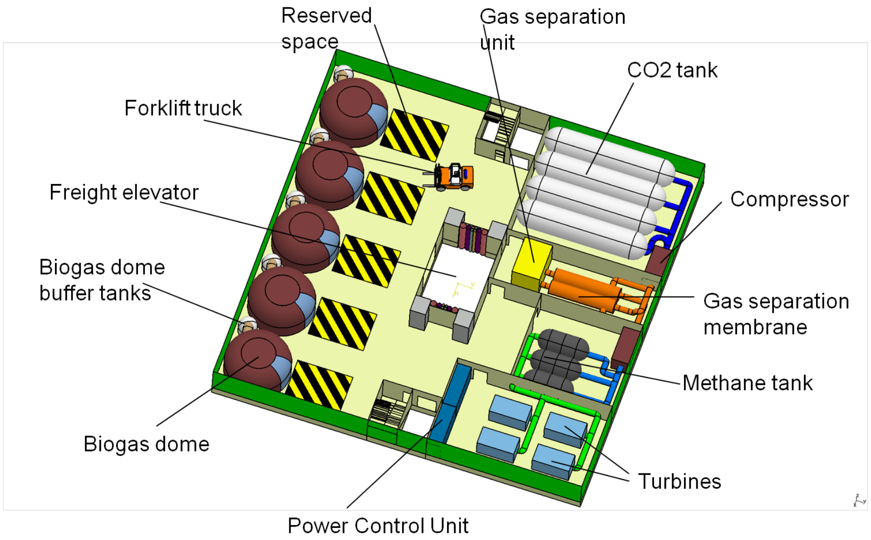


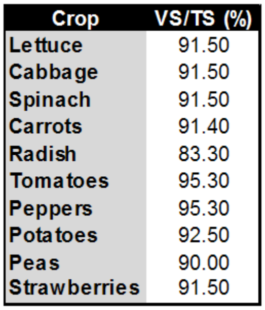
Figure 13.1.3: Plan of Floor 2



13.1.4 Bio-waste treatment

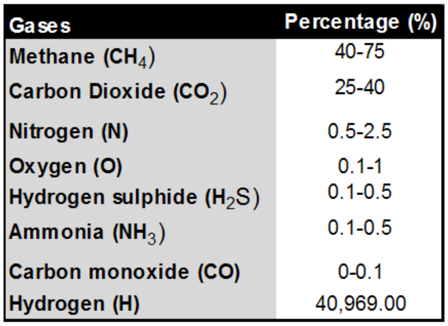
The amount of bio-gas which can be produced from bio-waste is determined from *[29]*, where the bio-gas yield in m^3/ton of Volatile Solid (VS), versus the Organic Loading Rate (OLR) has been discussed in detail. Based on information for CROPGEN [20], the Volatile to Total Solid ratio is presented in Table 13.1 for the ten crops selected for the Vertical Farm. The average value for these ten crops is calculated and yields that the Volatile Solids make up about 91.4% of the Total Solid bio-waste. Assuming that this value is somewhat lower for fish, an average value of 90% will be used for the initial calculations.

Table 13.1: Volatile Solid to Total Solid ratio for the Vertical Farm crops



Crop	VS/TS (%)
Lettuce	91.50
Cabbage	91.50
Spinach	91.50
Carrots	91.40
Radish	83.30
Tomatoes	95.30
Peppers	95.30
Potatoes	92.50
Peas	90.00
Strawberries	91.50

Table 13.2: Average bio-gas composition



Gases	Percentage (%)
Methane (CH_4)	40-75
Carbon Dioxide (CO_2)	25-40
Nitrogen (N)	0.5-2.5
Oxygen (O)	0.1-1
Hydrogen sulphide (H_2S)	0.1-0.5
Ammonia (NH_3)	0.1-0.5
Carbon monoxide (CO)	0-0.1
Hydrogen (H)	40,969.00

Source: [5]

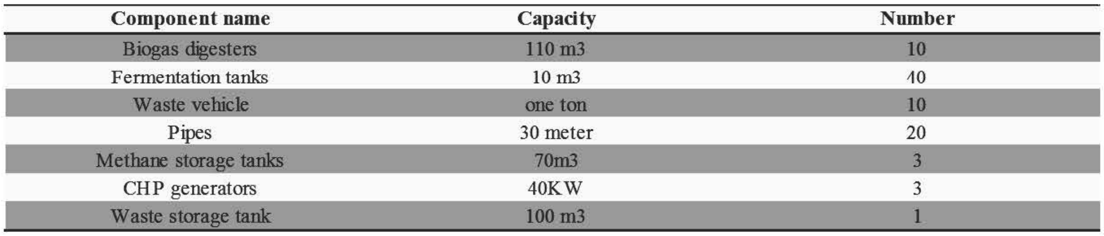
On an average the amount of waste coming into the Waste Management Floors each day is 7.11 tons. Since 90% of the Total Solids is Volatile Solids, the Vertical Farm produces 6.4 tons of VS per day. The Waste Management Floors have ten digesters, each with a volume of 110 m^3, leading to a total digester volume of 1100 m^3. The OLR can then be calculated to be: 6400 kg VS/day/1100 m^3 is: 5.82 kg VS/m^3/day. Based on *[29]*, it can be deduced that for an OLR of 5.82 kg VS/m^3/day, the bio-gas yield is about 480m^3/ton of VS. 6.4 tons of VS per day times 480 m^3 bio-gas per metric ton of VS results in 3072 m^3 of bio-gas. To determine the amount of methane and carbon dioxide production from the bio-gas yield, the specific composition of the bio-gas should be determined. Table 13.2 lists the average composition of bio-gas from various types of bio-waste. This makes it possible to calculate the amount of methane and carbon dioxide produced by the Vertical Farm. Assuming the bio-gas consists of 60% methane gives a production of 1843.2 m^3 of CH_4 per day. Additionally, using the assumption that 30% of the bio-gas is carbon dioxide, the Waste Management Floor produces

921.6 m^3 of CO_2.

13.2 List of Equipments

From the aforementioned design an equipment list is prepared as follows.

Table 13.3: List of equipments for Waste Management System



Component name	**Capacity**	**Number**
Biogas digesters	110 m3	10
Fermentation tanks	10 m3	40
Waste vehicle	one ton	10
Pipes	30 meter	20
Methane storage tanks	70m3	3
CHP generators	40KW	3
Waste storage tank	100 m3	1

Part III

Cost Analysis

Chapter 14

Capital Expenditure

In this chapter the capital expenditure for constructing a VF as per the system plan shall be discussed. This fixed cost pertains to the cost of the building and the equipments required for its operation. The costs are expressed in form of Annuity.

14.1 Cost of Building the Tower

A detailed explanation of the methodology, parameters and assumptions used for estimating the cost of the building is to be found in Appendix B. The Table 14.2 and 14.3 show an estimated cost of building the outer structure and also that of a single floor, assuming average land price in Berlin. This means that the cost of building a 37 story high VF is around 111.58 million Euros, an amount amortised over a period of 30 years.

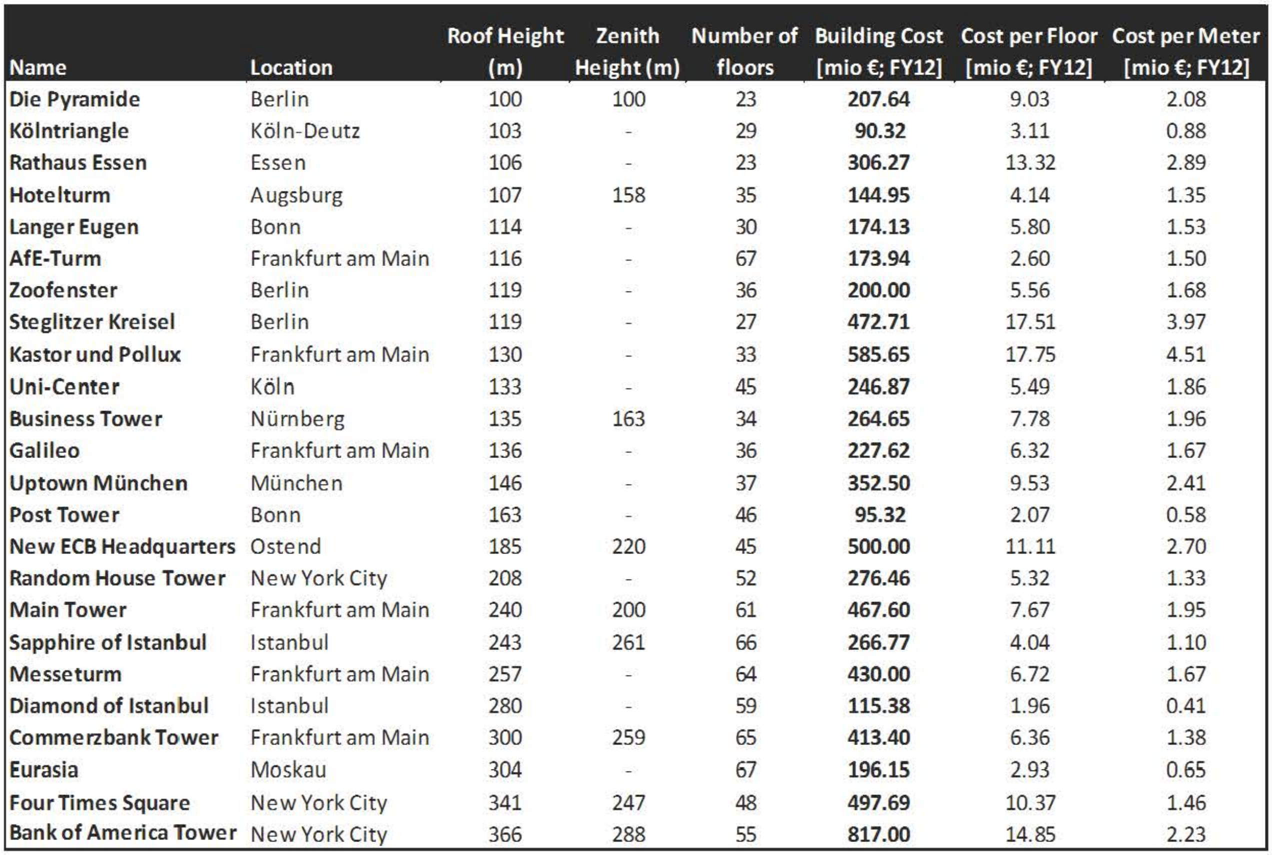
For comparison, the building costs of a couple of randomly chosen high rises from Europe and abroad are presented in Table 14.1[1]. One cannot compare the cost of a vertical farming tower with the building costs of the following buildings. They are meant for office or residential purpose and have very different standards. The VF on the other hand is meant to house crops, need not be aesthetically pleasing from inside and hence may be assumed to cost

---

[1] The costs have been inflation corrected to FY 2012, assuming USD 1.00 € 1.30 and DM 1.00 € 0.50.

considerably lower than these buildings. This is also the case, in spite of that, it does show us that our estimations, are quite in the realistic realm.

Table 14.1: Some high rises and their building cost



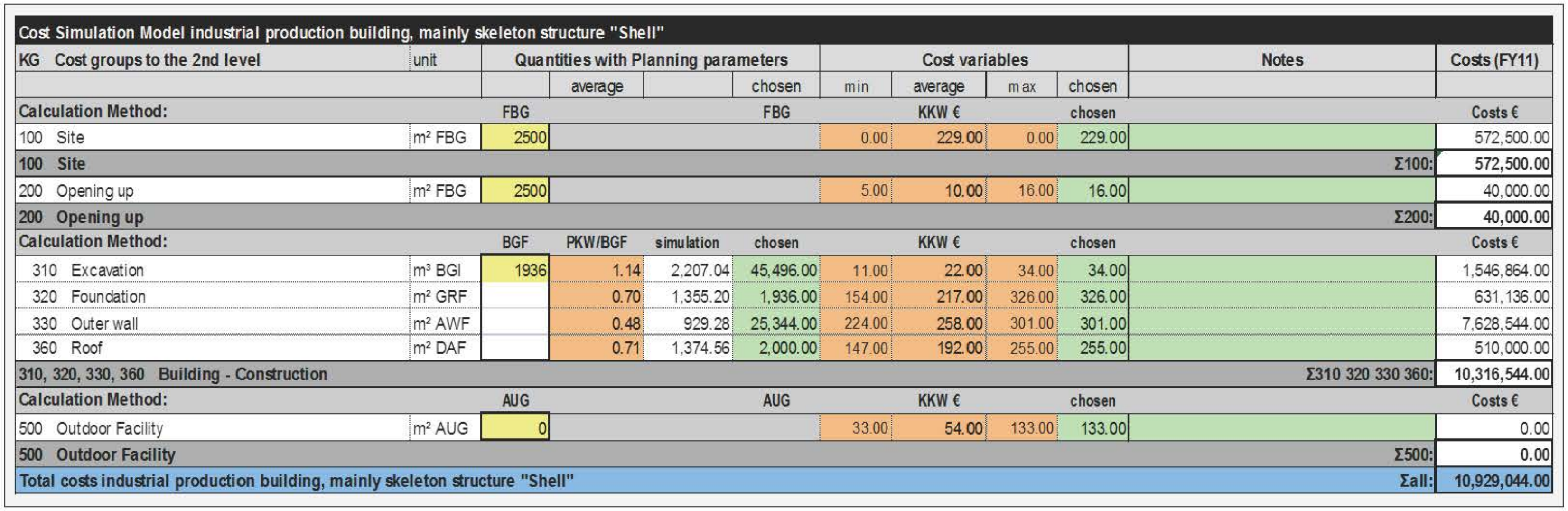
Name	Location	Roof Height (m)	Zenith Height (m)	Number of floors	Building Cost [mio €; FY12]	Cost per Floor [mio €; FY12]	Cost per Meter [mio €; FY12]
Die Pyramide	Berlin	100	100	23	**207.64**	9.03	2.08
Kölntriangle	Köln-Deutz	103	-	29	**90.32**	3.11	0.88
Rathaus Essen	Essen	106	-	23	**306.27**	13.32	2.89
Hotelturm	Augsburg	107	158	35	**144.95**	4.14	1.35
Langer Eugen	Bonn	114	-	30	**174.13**	5.80	1.53
AfE-Turm	Frankfurt am Main	116	-	67	**173.94**	2.60	1.50
Zoofenster	Berlin	119	-	36	**200.00**	5.56	1.68
Steglitzer Kreisel	Berlin	119	-	27	**472.71**	17.51	3.97
Kastor und Pollux	Frankfurt am Main	130	-	33	**585.65**	17.75	4.51
Uni-Center	Köln	133	-	45	**246.87**	5.49	1.86
Business Tower	Nürnberg	135	163	34	**264.65**	7.78	1.96
Galileo	Frankfurt am Main	136	-	36	**227.62**	6.32	1.67
Uptown München	München	146	-	37	**352.50**	9.53	2.41
Post Tower	Bonn	163	-	46	**95.32**	2.07	0.58
New ECB Headquarters	Ostend	185	220	45	**500.00**	11.11	2.70
Random House Tower	New York City	208	-	52	**276.46**	5.32	1.33
Main Tower	Frankfurt am Main	240	200	61	**467.60**	7.67	1.95
Sapphire of Istanbul	Istanbul	243	261	66	**266.77**	4.04	1.10
Messeturm	Frankfurt am Main	257	-	64	**430.00**	6.72	1.67
Diamond of Istanbul	Istanbul	280	-	59	**115.38**	1.96	0.41
Commerzbank Tower	Frankfurt am Main	300	259	65	**413.40**	6.36	1.38
Eurasia	Moskau	304	-	67	**196.15**	2.93	0.65
Four Times Square	New York City	341	247	48	**497.69**	10.37	1.46
Bank of America Tower	New York City	366	288	55	**817.00**	14.85	2.23

The Skyscraper Center - The Global Tall Building Database of CTBUH. [Online] Available: http://www.skyscrapercenter.com.

14.2 Cost of Equipments

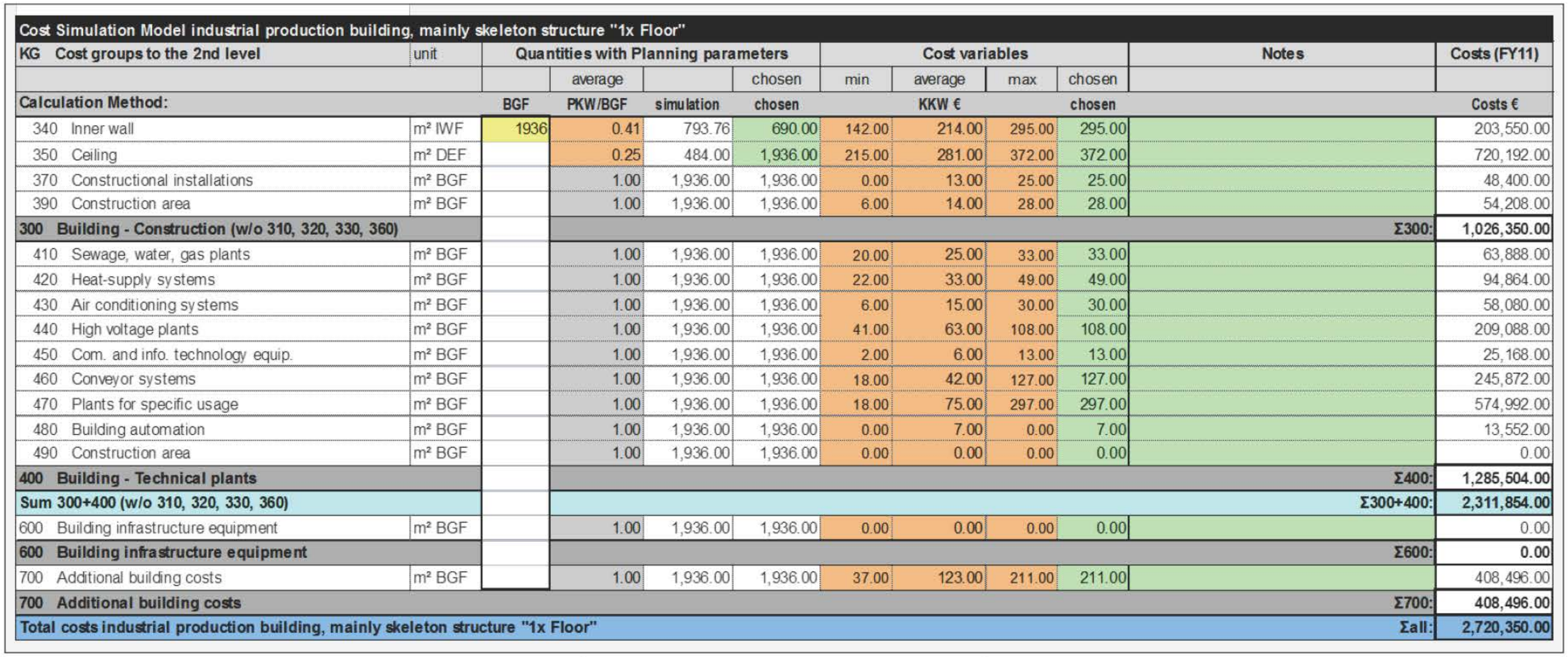
A cost summary of all the required equipments reported in Part II, brings us to a total cost of about 90.4 million Euros (see Figure: 14.4).

Table 14.2: Cost of outer shell

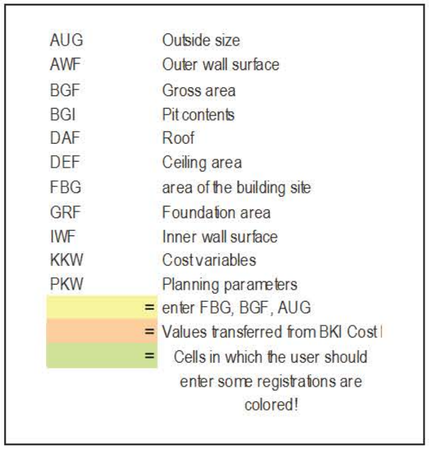


Cost Simulation Model industrial production building, mainly skeleton structure "Shell"											
KG Cost groups to the 2nd level	unit	Quantities with Planning parameters				Cost variables				Notes	Costs (FY11)
			average		chosen	min	average	max	chosen		
Calculation Method:		**FBG**			**FBG**		**KKW €**		**chosen**		**Costs €**
100 Site	m^2 FBG	2500				0.00	229.00	0.00	229.00		572,500.00
100 Site										**Σ100:**	**572,500.00**
200 Opening up	m^2 FBG	2500				5.00	10.00	16.00	16.00		40,000.00
200 Opening up										**Σ200:**	**40,000.00**
Calculation Method:		**BGF**	**PKW/BGF**	**simulation**	**chosen**		**KKW €**		**chosen**		**Costs €**
310 Excavation	m^3 BGI	1936	1.14	2,207.04	45,496.00	11.00	22.00	34.00	34.00		1,546,864.00
320 Foundation	m^2 GRF		0.70	1,355.20	1,936.00	154.00	217.00	326.00	326.00		631,136.00
330 Outer wall	m^2 AWF		0.48	929.28	25,344.00	224.00	258.00	301.00	301.00		7,628,544.00
360 Roof	m^2 DAF		0.71	1,374.56	2,000.00	147.00	192.00	255.00	255.00		510,000.00
310, 320, 330, 360 Building - Construction										**Σ310 320 330 360:**	**10,316,544.00**
Calculation Method:		**AUG**			**AUG**		**KKW €**		**chosen**		**Costs €**
500 Outdoor Facility	m^2 AUG	0				33.00	54.00	133.00	133.00		0.00
500 Outdoor Facility										**Σ500:**	**0.00**
Total costs industrial production building, mainly skeleton structure "Shell"										**Σall:**	**10,929,044.00**

Table 14.3: Cost of each floor

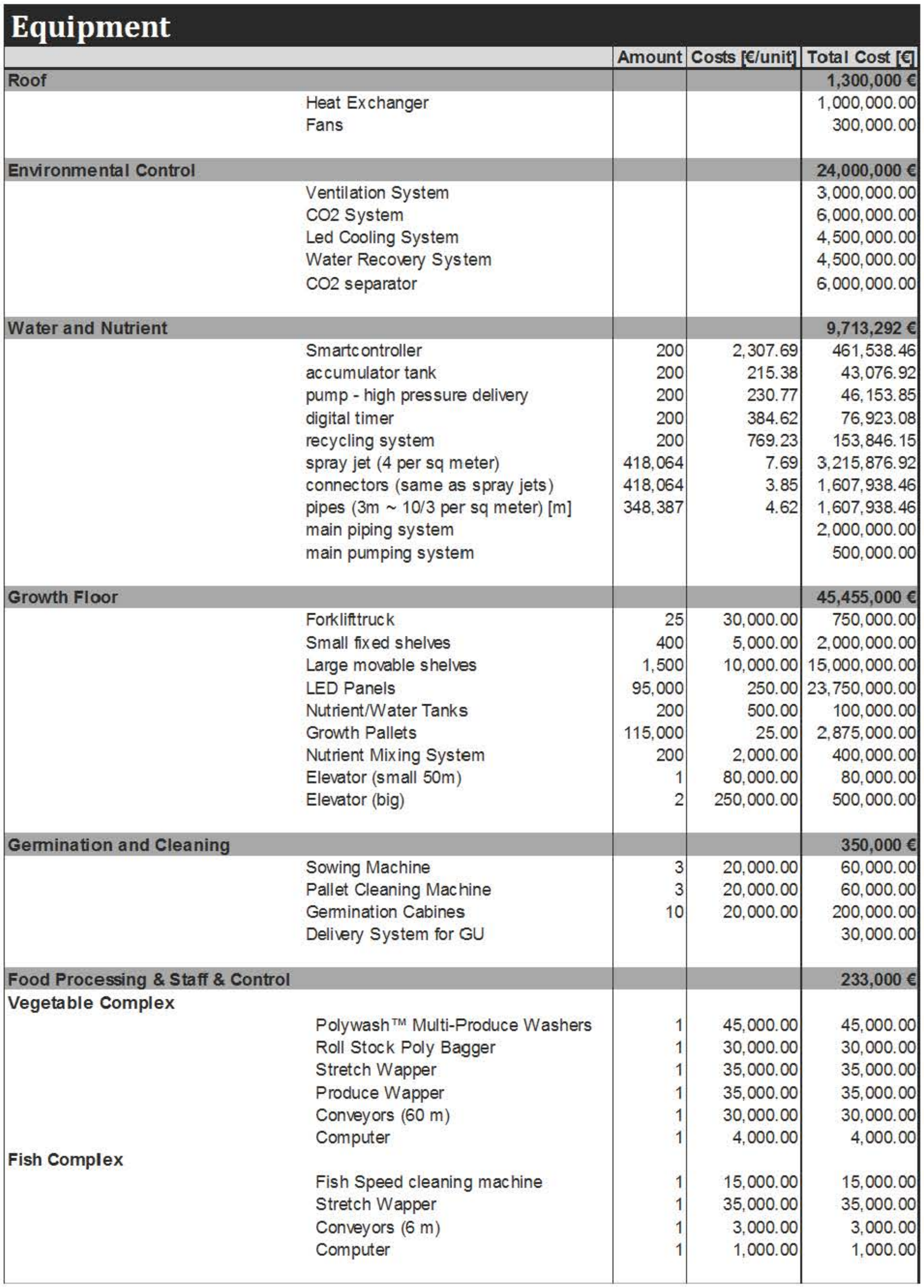


Cost Simulation Model industrial production building, mainly skeleton structure "1x Floor"												
KG	Cost groups to the 2nd level	unit	Quantities with Planning parameters				Cost variables				Notes	Costs (FY11)
				average		chosen	min	average	max	chosen		
Calculation Method:			BGF	PKW/BGF	simulation	chosen		KKW €		chosen		Costs €
340	Inner wall	m² IWF	1936	0.41	793.76	690.00	142.00	214.00	295.00	295.00		203,550.00
350	Ceiling	m² DEF		0.25	484.00	1,936.00	215.00	281.00	372.00	372.00		720,192.00
370	Constructional installations	m² BGF		1.00	1,936.00	1,936.00	0.00	13.00	25.00	25.00		48,400.00
390	Construction area	m² BGF		1.00	1,936.00	1,936.00	6.00	14.00	28.00	28.00		54,208.00
300	**Building - Construction (w/o 310, 320, 330, 360)**										**Σ300:**	**1,026,350.00**
410	Sewage, water, gas plants	m² BGF		1.00	1,936.00	1,936.00	20.00	25.00	33.00	33.00		63,888.00
420	Heat-supply systems	m² BGF		1.00	1,936.00	1,936.00	22.00	33.00	49.00	49.00		94,864.00
430	Air conditioning systems	m² BGF		1.00	1,936.00	1,936.00	6.00	15.00	30.00	30.00		58,080.00
440	High voltage plants	m² BGF		1.00	1,936.00	1,936.00	41.00	63.00	108.00	108.00		209,088.00
450	Com. and info. technology equip.	m² BGF		1.00	1,936.00	1,936.00	2.00	6.00	13.00	13.00		25,168.00
460	Conveyor systems	m² BGF		1.00	1,936.00	1,936.00	18.00	42.00	127.00	127.00		245,872.00
470	Plants for specific usage	m² BGF		1.00	1,936.00	1,936.00	18.00	75.00	297.00	297.00		574,992.00
480	Building automation	m² BGF		1.00	1,936.00	1,936.00	0.00	7.00	0.00	7.00		13,552.00
490	Construction area	m² BGF		1.00	1,936.00	1,936.00	0.00	0.00	0.00	0.00		0.00
400	**Building - Technical plants**										**Σ400:**	**1,285,504.00**
Sum 300+400 (w/o 310, 320, 330, 360)											**Σ300+400:**	**2,311,854.00**
600	Building infrastructure equipment	m² BGF		1.00	1,936.00	1,936.00	0.00	0.00	0.00	0.00		0.00
600	**Building infrastructure equipment**										**Σ600:**	**0.00**
700	Additional building costs	m² BGF		1.00	1,936.00	1,936.00	37.00	123.00	211.00	211.00		408,496.00
700	**Additional building costs**										**Σ700:**	**408,496.00**
Total costs industrial production building, mainly skeleton structure "1x Floor"											**Σall:**	**2,720,350.00**



AUG	Outside size
AWF	Outer wall surface
BGF	Gross area
BGI	Pit contents
DAF	Roof
DEF	Ceiling area
FBG	area of the building site
GRF	Foundation area
IWF	Inner wall surface
KKW	Cost variables
PKW	Planning parameters
🟨 =	enter FBG, BGF, AUG
🟧 =	Values transferred from BKI Cost I
🟩 =	Cells in which the user should enter some registrations are colored!

Table 14.4: Cost of equipments



Equipment		Amount	Costs [€/unit]	Total Cost [€]
Roof				**1,300,000 €**
	Heat Exchanger			1,000,000.00
	Fans			300,000.00
Environmental Control				**24,000,000 €**
	Ventilation System			3,000,000.00
	CO2 System			6,000,000.00
	Led Cooling System			4,500,000.00
	Water Recovery System			4,500,000.00
	CO2 separator			6,000,000.00
Water and Nutrient				**9,713,292 €**
	Smartcontroller	200	2,307.69	461,538.46
	accumulator tank	200	215.38	43,076.92
	pump - high pressure delivery	200	230.77	46,153.85
	digital timer	200	384.62	76,923.08
	recycling system	200	769.23	153,846.15
	spray jet (4 per sq meter)	418,064	7.69	3,215,876.92
	connectors (same as spray jets)	418,064	3.85	1,607,938.46
	pipes (3m ~ 10/3 per sq meter) [m]	348,387	4.62	1,607,938.46
	main piping system			2,000,000.00
	main pumping system			500,000.00
Growth Floor				**45,455,000 €**
	Forklifttruck	25	30,000.00	750,000.00
	Small fixed shelves	400	5,000.00	2,000,000.00
	Large movable shelves	1,500	10,000.00	15,000,000.00
	LED Panels	95,000	250.00	23,750,000.00
	Nutrient/Water Tanks	200	500.00	100,000.00
	Growth Pallets	115,000	25.00	2,875,000.00
	Nutrient Mixing System	200	2,000.00	400,000.00
	Elevator (small 50m)	1	80,000.00	80,000.00
	Elevator (big)	2	250,000.00	500,000.00
Germination and Cleaning				**350,000 €**
	Sowing Machine	3	20,000.00	60,000.00
	Pallet Cleaning Machine	3	20,000.00	60,000.00
	Germination Cabines	10	20,000.00	200,000.00
	Delivery System for GU			30,000.00
Food Processing & Staff & Control				**233,000 €**
Vegetable Complex				
	Polywash™ Multi-Produce Washers	1	45,000.00	45,000.00
	Roll Stock Poly Bagger	1	30,000.00	30,000.00
	Stretch Wapper	1	35,000.00	35,000.00
	Produce Wapper	1	35,000.00	35,000.00
	Conveyors (60 m)	1	30,000.00	30,000.00
	Computer	1	4,000.00	4,000.00
Fish Complex				
	Fish Speed cleaning machine	1	15,000.00	15,000.00
	Stretch Wapper	1	35,000.00	35,000.00
	Conveyors (6 m)	1	3,000.00	3,000.00
	Computer	1	1,000.00	1,000.00

Waste Management				**8,825,000 €**
	Domes	10	20,000.00	200,000.00
	Storage tanks	10	5,000.00	50,000.00
	Trash carts	5	15,000.00	75,000.00
	Pipes			1,000,000.00
	Biogas generators	3	1,000,000.00	3,000,000.00
	Fertilizer extractor	1	1,500,000.00	1,500,000.00
	Gas Cleaning			3,000,000.00
Fish Farm				**505,900 €**
Tanks				
	Culture tanks	15	4,000.00	60,000.00
	Growout tanks	33	7,000.00	231,000.00
Water Treatment				
	Liqui-Cell Membrane contractors	6	1,500.00	9,000.00
	Nitrification and denitrification system	6	2,000.00	12,000.00
	Oxygenation system	6	1,000.00	6,000.00
	Sludge removal system	16	7,000.00	112,000.00
	Solid waste removal system	6	500.00	3,000.00
	UV Lighting (Bacteria Annihilation)	6	400.00	2,400.00
Sensors				
	Alkalinity sensors	16	200.00	3,200.00
	Ammonia sensor	16	150.00	2,400.00
	CO2 sensor	16	100.00	1,600.00
	Nitrogen Oxide levels	16	100.00	1,600.00
	Oxygen sensor	16	100.00	1,600.00
	pH sensor	16	150.00	2,400.00
	Thermonitor	16	50.00	800.00
	Water flow sensor	16	70.00	1,120.00
	Water level sensor	16	40.00	640.00
Logistics				
	Feeding system	16	300.00	4,800.00
	Hapas	800	30.00	24,000.00
	Heating system	16	300.00	4,800.00
	Low level lighting	16	40.00	640.00
	Pump	32	400.00	12,800.00
	Sorting table	12	300.00	3,600.00
	Hapas moving crane	3	1,500.00	4,500.00

Chapter 15

Operational Expenditure

15.1 Power Costs

As seen in the Tables: 15.1[1] through 15.4, the power costs sums up to around 5.4 million Euros a year (refer to Table: 15.4, which gives the expense for a month)[2]. This is only when power is bought from external sources and could hence be considered as the worst scenario in light of the discussion in 18.4.2. There are further cost saving measures undertaken, like lighting at night, when the tariffs are low, use of shutter factor and consideration of development factor (discussed at length in the section of "Lighting systems"). However, more accurate estimations and better cost saving measures remain a domain of further research.

A word of caveat. It was quite difficult to simulate the energy requirement for Environmental control through a mere Concurrent Engineering study. There are too many open ended questions that cannot be answered without experimentation. Literature on this pertains mainly to space research and are not easily adaptable to terrestrial conditions. Terrestrial condition as such is varied, of which Berlin weather is definitely not a representative. Owing to these reasons, only cooling of the heat generated by the LED panels was taken into consideration. It was assumed that 60% of the power required for lighting is the power

---

[1] The system is designed to run at night for cheap electricity

[2] The cost estimation is derived on the basis of information found in http://de.wikipedia.org/wiki/Strompreis and http://www.tengelmann-energie.de/Hochtarif.690.0.html

required for environmental regulation.

Table 15.1: Power demand for lighting needs

Lighting	Operating Time [h]	Energy Demand per floor per day [kWh]	Number of Floors	Total Energy Demand [kWh/day]	Total Energy Demand [kWh/month]	Total Energy Demand (incl. Shutter and Development Factor) [kWh/month]	Power Consumption High Tarif [kWh]	Power Consumption Low Tarif [kWh]
Carrots	16	2,954	2	5,908	177,240	129,607	64,803	64,803
Radish	16	3,692	1	3,692	110,760	80,993	40,497	40,497
Cabbage	16	3,692	2	7,384	221,520	161,987	80,993	80,993
Lettuce	16	4,431	4	17,724	531,720	388,820	194,410	194,410
Spinach	16	4,431	1	4,431	132,930	97,205	48,603	48,603
Potatoes	12	1,824	5	9,120	273,600	200,070	66,690	133,380
Tomatoes	12	3,519	3	10,557	316,710	231,594	77,198	154,396
Pepper	12	3,519	2	7,038	211,140	154,396	51,465	102,931
Pea	12	2,346	4	9,384	281,520	205,862	68,621	137,241
Strawberry	12	4,301	1	4,301	129,030	94,353	31,451	62,902
Sum:						**1744887**	**724731**	**1020156**

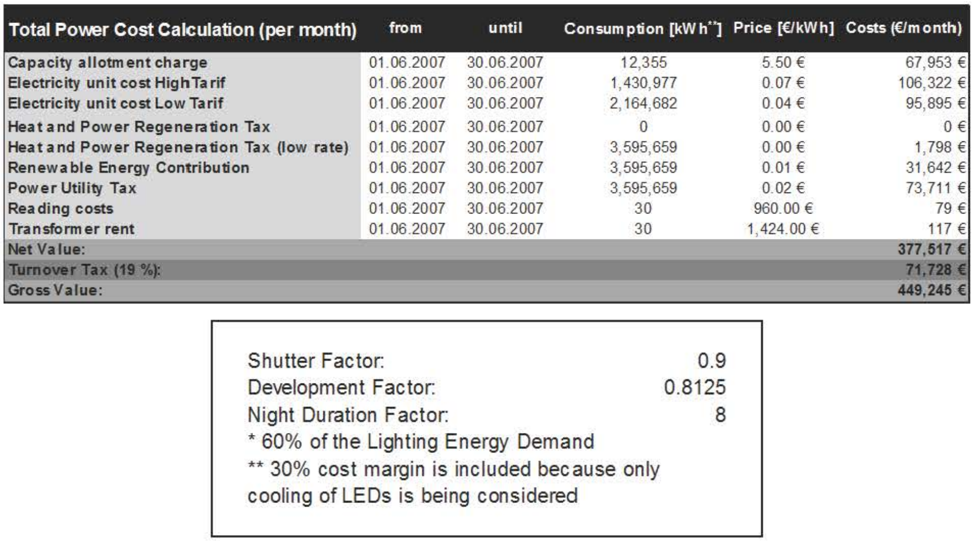
Table 15.2: Power demand for Environmental Regulation

Environmental Control *	Operating Time [h]	Energy Demand per floor per day [kWh]	Number of Floors	Total Energy Demand [kWh/day]	Total Energy Demand [kWh/month]	Power Consumption High Tarif [kWh]	Power Consumption Low Tarif [kWh]
Carrots	16	1,772	2	3,545	106,344	53,172	53,172
Radish	16	2,215	1	2,215	66,456	33,228	33,228
Cabbage	16	2,215	2	4,430	132,912	66,456	66,456
Lettuce	16	2,659	4	10,634	319,032	159,516	159,516
Spinach	16	2,659	1	2,659	79,758	39,879	39,879
Potatoes	12	1,094	5	5,472	164,160	54,720	109,440
Tomatoes	12	2,111	3	6,334	190,026	63,342	126,684
Pepper	12	2,111	2	4,223	126,684	42,228	84,456
Pea	12	1,408	4	5,630	168,912	56,304	112,608
Strawberry	12	2,581	1	2,581	77,418	25,806	51,612
Sum:					**1431702**	**594651**	**837051**
Sum with 30%margin:*						**773046**	**1088166**

Table 15.3: Power demand for Miscellaneous needs

Miscellaneous	Operating Time [h]	Energy Demand per floor per day [kWh]	Number of Floors	Total Energy Demand [kWh/day]	Total Energy Demand [kWh/month]	Total Energy Demand (incl. Shutter and Development	Power Consumption High Tarif [kWh]
Animal	24	120	3	360	10,800	7,200	3,600
Waste	8	-2,500	2	-5,000	-150,000	-150,000	0
Water/Nutrient	24	200	1	200	6,000	4,000	2,000
Food Processing	-	146	-	146	4,380	0	4,380
Plants	8	124	1	124	3,720	0	3,720
Fish	4	22	1	22	660	0	660
Germination & Cleaning	24	3,600	1	3,600	108,000	72,000	36,000
Super Market & Delivery	8	200	1	200	6,000	0	6,000
Sum:					**-10440**	**-66800**	**56360**

Table 15.4: Power Cost



Total Power Cost Calculation (per month)	from	until	Consumption [kWh**]	Price [€/kWh]	Costs (€/month)
Capacity allotment charge	01.06.2007	30.06.2007	12,355	5.50 €	67,953 €
Electricity unit cost High Tarif	01.06.2007	30.06.2007	1,430,977	0.07 €	106,322 €
Electricity unit cost Low Tarif	01.06.2007	30.06.2007	2,164,682	0.04 €	95,895 €
Heat and Power Regeneration Tax	01.06.2007	30.06.2007	0	0.00 €	0 €
Heat and Power Regeneration Tax (low rate)	01.06.2007	30.06.2007	3,595,659	0.00 €	1,798 €
Renewable Energy Contribution	01.06.2007	30.06.2007	3,595,659	0.01 €	31,642 €
Power Utility Tax	01.06.2007	30.06.2007	3,595,659	0.02 €	73,711 €
Reading costs	01.06.2007	30.06.2007	30	960.00 €	79 €
Transformer rent	01.06.2007	30.06.2007	30	1,424.00 €	117 €
Net Value:					377,517 €
Turnover Tax (19 %):					71,728 €
Gross Value:					449,245 €

Shutter Factor:	0.9
Development Factor:	0.8125
Night Duration Factor:	8

* 60% of the Lighting Energy Demand

** 30% cost margin is included because only cooling of LEDs is being considered

15.2 Seed, Feed and Fertilizer Costs

Seeds: The seed costs at wholesale rates are not publicly available on the net or in KTBL handbooks for these crops. Therefore the approximations had to be based on the price of seeds meant for the purpose of gardening. For wholesale purposes, like the one in this case the price should be considerably low. For estimated amount and corresponding cost of seeds, refer to Table 15.5[3].

Fertilisers: The Table: 15.6 shows the fertiliser requirement and associated costs. However, since the water is recycled, and the bio-wastes are re-utilised for composting and generation of plant nutrients, for the purpose of cost estimation only 50% of the undermentioned amount is accounted.

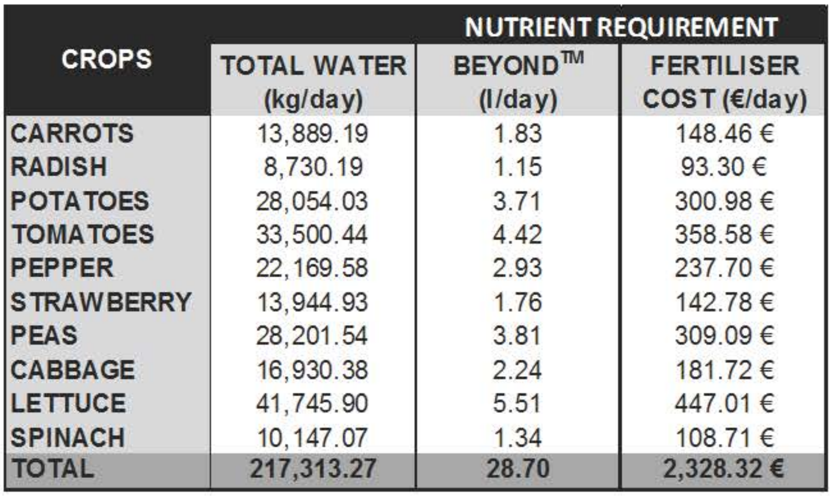
---

[3] The cost estimation is derived loosely on the basis of cost of seeds for gardening purposes found in http://www.alibaba.com/ and http://www.ktbl.de/

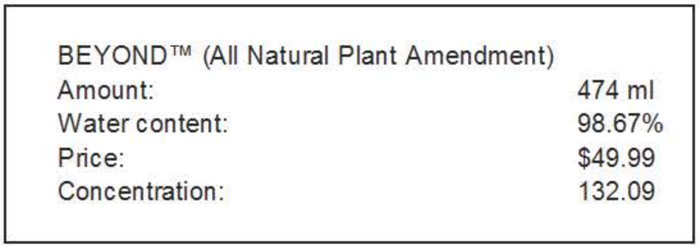
Table 15.5: Seed Costs

Seed Costs	Plant Spacing [m]	Plant Density [plants/m^2]	Area per floor [m^2]	Number of Floors	Total Growing Area [m^2]/a	Plants [plants/period]	Plants [plants/a]	Cost [€/seed]	Cost [€/a]
Carrots	0.20	25	3672.00	2	36,720.00	183,600	918,000	4.87 €	4,472.31 €
Radish	0.20	25	4590.00	1	67,128.75	114,750	1,678,219	4.87 €	8,175.94 €
Potatoes	0.30	11	1836.00	5	27,540.00	102,000	306,000	24.15 €	7,389.90 €
Tomatoes	0.21	23	3672.00	3	49,572.00	249,796	1,124,082	6.33 €	7,120.88 €
Pepper	0.30	11	3672.00	2	33,048.00	81,600	367,200	18.27 €	6,708.46 €
Strawberry	0.46	5	5508.00	1	24,786.00	26,030	117,136	6.92 €	810.94 €
Peas	0.51	4	2754.00	4	55,080.00	42,353	211,765	7.31 €	1,547.51 €
Cabbage	0.38	7	4590.00	2	41,310.00	63,573	286,080	2.92 €	836.23 €
Lettuce	0.21	23	5508.00	4	286,416.00	499,592	6,494,694	0.97 €	6,328.16 €
Spinach	0.31	10	5508.00	1	66,784.50	57,315	694,948	1.46 €	1,015.69 €
				Total Area [m^2]:	**688,385.25**			Total Costs [€/a]:	**44,406.03 €**

Table 15.6: Fertiliser Costs



CROPS		NUTRIENT REQUIREMENT	
	TOTAL WATER (kg/day)	BEYOND™ (l/day)	FERTILISER COST (€/day)
CARROTS	13,889.19	1.83	148.46 €
RADISH	8,730.19	1.15	93.30 €
POTATOES	28,054.03	3.71	300.98 €
TOMATOES	33,500.44	4.42	358.58 €
PEPPER	22,169.58	2.93	237.70 €
STRAWBERRY	13,944.93	1.76	142.78 €
PEAS	28,201.54	3.81	309.09 €
CABBAGE	16,930.38	2.24	181.72 €
LETTUCE	41,745.90	5.51	447.01 €
SPINACH	10,147.07	1.34	108.71 €
TOTAL	**217,313.27**	**28.70**	**2,328.32 €**



BEYOND™ (All Natural Plant Amendment)

Amount:	474 ml
Water content:	98.67%
Price:	$49.99
Concentration:	132.09

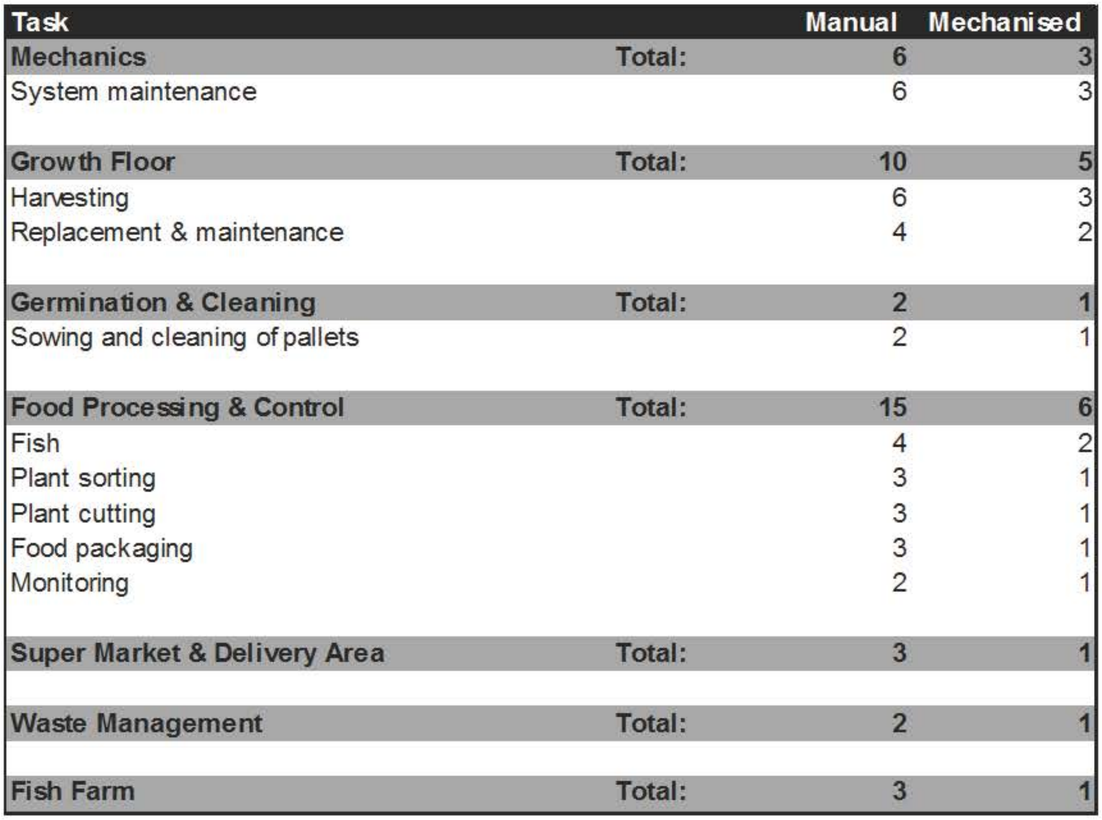
Source: [10]

Fish feed: As seen in Table 8.1 and 8.2 a fish consumes 191% of its total body mass as feed in its entire life cycle. However, Tilapia being versatile the non edible plant biomass can be fed. Therefore only 50% of the total feed requirement is accounted for in the cost estimation. Since a total of 137 tons of fish fillet is obtained from 341 tons of total fish biomass, approximately 651 tons of feed is consumed by the fishes per year. Since about 50% of this can be obtained for the bi-products of the VF the rest amount of 326 tons is bought at an approximate rate of 0.39 €/kg from the market totalling to an amount of 127,000 €/year.

15.3 Personnel Costs

This is an approximation of the personnel requirement of the VF. In this there are two scenarios, one is a predominantly manual production system with only requisite mechanisation (requiring a total of 41 personnels), while the other is a highly mechanised system where the personnel requirement is assumed to be about half of the former (requiring a total of 18 personnels). The cost of labour is taken at an average of 50,000 €/year per personnel. The estimations are shown in the Table: 15.7. The labour requirement for the farm which is the largest single system, is discussed in detail in the designated section. Apparently, the food processing section requires the maximum number of personnel for its daily operations. However, since most of them are unskilled labour, they can be substituted to other systems when the work load demands so.

Table 15.7: Personnel requirement



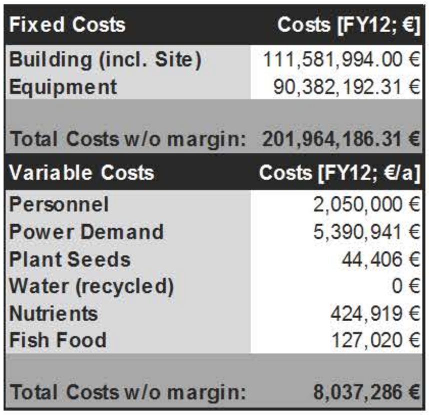
Task		Manual	Mechanised
Mechanics	**Total:**	**6**	**3**
System maintenance		6	3
Growth Floor	**Total:**	**10**	**5**
Harvesting		6	3
Replacement & maintenance		4	2
Germination & Cleaning	**Total:**	**2**	**1**
Sowing and cleaning of pallets		2	1
Food Processing & Control	**Total:**	**15**	**6**
Fish		4	2
Plant sorting		3	1
Plant cutting		3	1
Food packaging		3	1
Monitoring		2	1
Super Market & Delivery Area	**Total:**	**3**	**1**
Waste Management	**Total:**	**2**	**1**
Fish Farm	**Total:**	**3**	**1**

Chapter 16

Total Production Cost

Production cost is the sum total of the fixed and variable costs per year. This is supposed to be the end result of the Concurrent Engineering Study as well as the Cost Analysis. The quotient of the total cost of production and the total edible biomass produced in a year gives us a rough estimate of the economic feasibility of the entire enterprise. It also helps us make an educated guess regarding the geographical and economic regions where this technology might find home. However, the variables are numerous, assumptions are plentiful and all of them need to be revised before embarking on a region specific economic analysis and drawing conclusions on its basis. However, in the middle of Berlin, the production cost is:

Table 16.1: Production Cost



Fixed Costs	**Costs [FY12; €]**
Building (incl. Site)	111,581,994.00 €
Equipment	90,382,192.31 €
Total Costs w/o margin:	**201,964,186.31 €**
Variable Costs	**Costs [FY12; €/a]**
Personnel	2,050,000 €
Power Demand	5,390,941 €
Plant Seeds	44,406 €
Water (recycled)	0 €
Nutrients	424,919 €
Fish Food	127,020 €
Total Costs w/o margin:	**8,037,286 €**

16.1 Cost Scenarios

Just as the variables the scenarios are innumerable. However, a couple of them have been reported in the Table: 16.2. The first is with respect to the building costs. In one case the building is supposed to have a life of 30 years with no salvage value at all, since it is assumes to be in Berlin the other plausible scenarios is to assign it a salvage value of approximately 1.2 million Euros for the land and other salvageable materials. The second is with respect to the labour requirement. As mentioned above, the first assumption is a highly mechanised system requiring only 18 personnel while the other requires 41 of them. The third is with respect to the production technology, simple hydroponics or cultivation with elevated CO_2 or aeroponics. The corresponding yield of crops under the various scenarios are reported in Table 7.2. The fourth and the fifth are of similar nature. They pertain to simulation of production costs with various combinations of cost margins for fixed and variable costs. The values are 10% for low, 20% for medium and 30% for high cost margins.

These simulations are done on the basis of the set of assumption mentioned above. As seen in the table, under best scenario, which in itself is a conservative one, the cost of producing edible biomass in this system is around 3.17 €/kg. In the worst case, that is with no salvage value, high labour requirement, hydroponic system, and high cost margins, it takes around 6.32 €/kg of organic fruits, vegetables and animal protein.

The simulations also show that it is most probable that the costs lie between 3.50 €/kg and 4.00 €/kg (44% of cases), followed by the class between 4.50 €/kg and 5.00 €/kg (22% of cases), 5.50 €/kg to 6.00 €/kg (17%), under 3.00 €/kg (12%) and above 6.00 €/kg (5% of cases).

Table 16.2: Scenarios of cost of producing unit biomass

BUILDING PARAMETERS	PRODUCTION PARAMETERS	PRODUCTION TECHNOLOGY	BUILDING COST MARGIN	RECURRENT COST MARGIN	COSTS OF PRODUCTION [€/kg]:
WITH SALVAGE VALUE	MECHANISED	Yield With Aeroponics [t/a]	LOW	low	3.17 €
				middle	3.29 €
				high	3.40 €
			MIDDLE	low	3.34 €
				middle	3.46 €
				high	3.58 €
			HIGH	low	3.51 €
				middle	3.63 €
				high	3.75 €
		Yield With Elevated CO2 [t/a]	LOW	low	3.88 €
				middle	4.02 €
				high	4.17 €
			MIDDLE	low	4.09 €
				middle	4.23 €
				high	4.38 €
			HIGH	low	4.30 €
				middle	4.44 €
				high	4.59 €
		Normal Yield [t/a]	LOW	low	5.00 €
				middle	5.19 €
				high	5.37 €
			MIDDLE	low	5.27 €
				middle	5.46 €
				high	5.64 €
			HIGH	low	5.54 €
				middle	5.73 €
				high	5.91 €
	MANUAL	Yield With Aeroponics [t/a]	LOW	low	3.39 €
				middle	3.52 €
				high	3.66 €
			MIDDLE	low	3.56 €
				middle	3.69 €
				high	3.83 €
			HIGH	low	3.73 €
				middle	3.86 €
				high	4.00 €
		Yield With Elevated CO2 [t/a]	LOW	low	4.14 €
				middle	4.31 €
				high	4.48 €
			MIDDLE	low	4.35 €
				middle	4.52 €
				high	4.69 €
			HIGH	low	4.56 €
				middle	4.73 €
				high	4.90 €
		Normal Yield [t/a]	LOW	low	5.34 €
				middle	5.56 €
				high	5.77 €
			MIDDLE	low	5.61 €
				middle	5.83 €
				high	6.04 €
				low	5.88 €

BUILDING PARAMETERS	PRODUCTION PARAMETERS	PRODUCTION TECHNOLOGY	BUILDING COST MARGIN	RECURRENT COST MARGIN	COSTS OF PRODUCTION [€/kg]:
			HIGH	middle	6.10 €
				high	6.31 €
WITHOUT SALVAGE VALUE	MECHANISED	Yield With Aeroponics [t/a]	LOW	low	3.17 €
				middle	3.29 €
				high	3.41 €
			MIDDLE	low	3.34 €
				middle	3.46 €
				high	3.58 €
			HIGH	low	3.52 €
				middle	3.63 €
				high	3.75 €
		Yield With Elevated CO2 [t/a]	LOW	low	3.89 €
				middle	4.03 €
				high	4.17 €
			MIDDLE	low	4.09 €
				middle	4.24 €
				high	4.38 €
			HIGH	low	4.30 €
				middle	4.45 €
				high	4.59 €
		Normal Yield [t/a]	LOW	low	5.01 €
				middle	5.19 €
				high	5.38 €
			MIDDLE	low	5.28 €
				middle	5.46 €
				high	5.65 €
			HIGH	low	5.55 €
				middle	5.73 €
				high	5.92 €
	MANUAL	Yield With Aeroponics [t/a]	LOW	low	3.39 €
				middle	3.53 €
				high	3.66 €
			MIDDLE	low	3.56 €
				middle	3.70 €
				high	3.84 €
			HIGH	low	3.73 €
				middle	3.87 €
				high	4.01 €
		Yield With Elevated CO2 [t/a]	LOW	low	4.15 €
				middle	4.32 €
				high	4.49 €
			MIDDLE	low	4.36 €
				middle	4.53 €
				high	4.69 €
			HIGH	low	4.57 €
				middle	4.74 €
				high	4.90 €
		Normal Yield [t/a]	LOW	low	5.35 €
				middle	5.57 €
				high	5.78 €
			MIDDLE	low	5.62 €
				middle	5.83 €

BUILDING PARAMETERS	PRODUCTION PARAMETERS	PRODUCTION TECHNOLOGY	BUILDING COST MARGIN	RECURRENT COST MARGIN	COSTS OF PRODUCTION [€/kg]:
				high	6.05 €
			HIGH	low	5.89 €
				middle	6.10 €
				high	6.32 €

ASSUMPTIONS

PRODUCTION PARAMETERS	**FACTOR**
Yield With Aeroponics [t/a]	1.4
Yield With Elevated CO2 [t/a]	1.3
Normal Yield [t/a]	1

PRODUCTION TECHNOLOGY	**FACTOR**
Mechanised	0.5
Manual	1

EXCHANGE RATE

$ TO €	1.3

INTEREST AND DURATION

i=	3.00%
T=	30 a

COST MARGINS

low	10%
middle	20%
high	30%

SALVAGE VALUE

FACTOR	**AMOUNT**
Land	771,643.50 €
Others	500,000.00 €
SALVAGE VALUE	1,271,643.50 €
W/O SALVAGE VALUE	0.00 €

Part IV

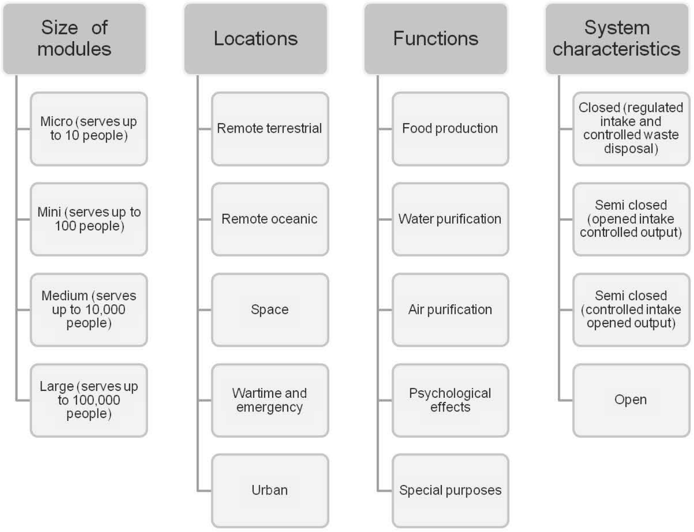
Market Analysis

Chapter 17

Market segmentation

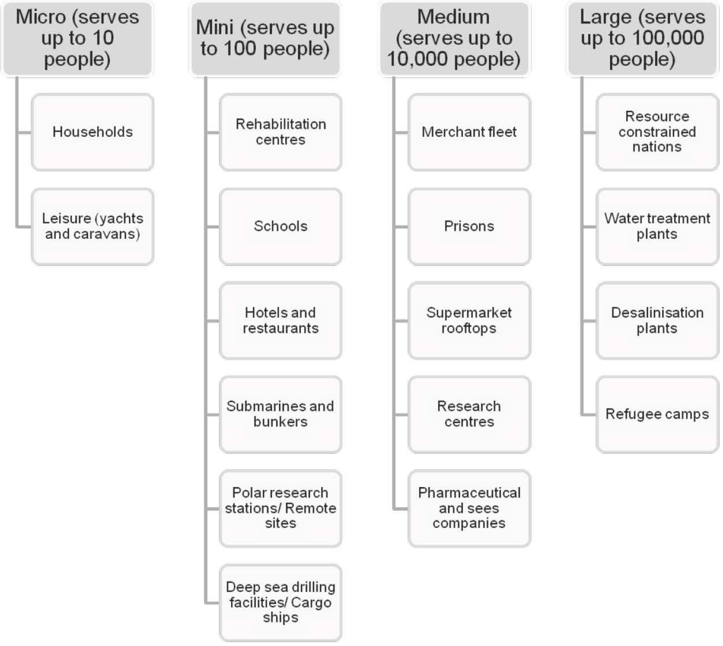
The technology developed by DLR-ISS in Bremen mainly with focus on food production for space missions. It includes but is not exclusively for Vertical farming. Although this study is meant for study of market strategy for vertical farms, it is appropriate to discuss the technology and its application with respect to the various market segments. The markets for high density bio-regenerative modules, developed in Bremen can be classified on the basis of its size, location, function and system characteristics as shown in Figure 17.0.1. The different forms of classifications are usable depending on the type of stake holder. For example Governments and Policy makers might be more interested in the classification of the product based on location features. Town planners might be more interested in functional classifications. While engineers and technological firms with interest in producing such modules would like a classification based on the system characteristics. For the purpose of this study, however, the classification based on size is of relevance, and hence a detailed schematic representation has been provided in Figure 17.0.2. As is evident, this study solely focuses on the fourth segment namely, large systems designed to cater to the needs of up to 100,000 people in a city or to address food sovereignty of resource constrained nations.

Figure 17.0.1: Schematic representation of market segments



Of this segment, the market opportunity and marketing strategy for food production modules will be studied. The newly developed technology has been applied in Vertical farms. The existing designs (like solar power plants) will be revisited and reconsidered to accommodate the technology developed by DLR-ISS in order to give it a unique selling point in the market.

Figure 17.0.2: Market classification on the basis of system size



Chapter 18

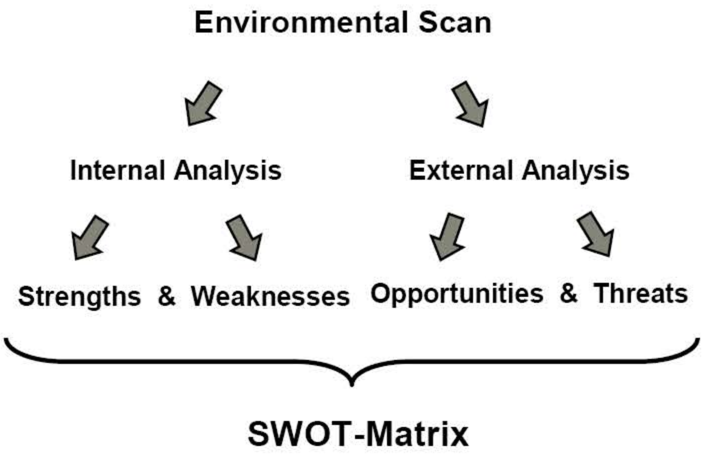
SWOT Analysis

A SWOT analysis is being used to exploit different factors of vertical farming. SWOT stands for strengths, weaknesses, opportunities and threats. It is a simple but systematic framework for appraising the intrinsic and institutional environment of a technology or business proposition. For the process of strategic planning, the SWOT analysis is an early but important "first step" in business planning. The framework originated from the Stanford Research Institute by Albert S. Humphrey and has dominated strategic plans since 1950 [8].

18.1 Theory

The SWOT analysis method is also effective to carry out market assessments of projects. The SWOT analysis can be the first step in identifying potential market opportunities. The SWOT analysis is only one of many tools that should be used in an organization's strategic planning process. There are a number of methods of environmental analysis like the PEST analysis (political, economic, social and technology analysis) or the Porter's Five-Forces framework [69].

Figure 18.1.1: Procedure algorithm for the SWOT analysis



Starting from an environmental scan (see Figure 18.1.1) two sub analysis need to be developed: the analysis of the internal situation and its strengths and weaknesses, as well as the external environment and its opportunities and threats. The internal situation describes the main product advantages and disadvantages, mainly in comparison to the main competing product (conventional agriculture in this case). In other words, the Strengths- Weakness analysis (SW-analysis) looks at the total output of the system as a self affected good. The external Opportunities-Threats analysis (OT-analysis) examines the external environment. Mostly those factors cannot be influenced directly through management actions. Opportunities and threats are anticipated future pathways and should be described in a dynamic sense, considering the current situations, existing threats, unexploited opportunities as well as probable trends [17].

Quantitative SWOT Analysis: The results of the different aspects are grouped together in a sort of benchmark test. Here, every aspect is evaluated and rated with a score. The score allocation throughout the SWOT-analysis is based on the available data. The weight of each aspect reflects an indication of an advantage or disadvantage of the vertical farming system relative to conventional agriculture. The OT-analysis uses the same score allocation principle. Thereby, the range of numbers from -5 to +5 is usually chosen, where +5 indicates a high strength (or high opportunity) and -5 indicates a high weakness (or high threat). The end results of the SWOT-analysis are usually displayed in a 2x2 matrix, where the main elements of each internal and external scan are worked out.

Qualitative SWOT Analysis: Sine the above mentioned benchmarking is difficult in case of a non-existing technology like VF, one has to resort to qualitative analysis, purely based on logical argument. Based on the environmental analysis, several strategies can be developed to:

- Use strengths to maximize opportunities.
- Use strengths to minimize threats.
- Minimize weaknesses by taking advantage of opportunities.
- Minimize weaknesses and avoid threats.

The VF is compared to conventional farming since it is the main competitor to vertical farming. In this regard first the internal and the external factors are identified. One of the back-stays of SWOT analysis is survey; customer survey, competitor survey, market survey, institutional survey to name a few. In this case such surveys are not possible since this technology is new, market is close to non existent, policies are not in place and public awareness is minimal. Therefore we have to settle for heuristics, internet surveys and concurrent engineering studies to quantify the parameters of the SWOT analysis.

18.2 Internal Analysis

The intrinsic factors of vertical agriculture, that may be controlled by within the system feature in the internal analysis. These include both positive and negative features, which contribute towards its strengths and weaknesses.

18.2.1 Strengths

The strengths or advantages of vertical farming is presently commonplace in print and online media, although peer reviewed scientific work is not available. One of the sources of positive information on vertical farming with almost no documentation of any of its short comings is the website of Prof. Dickson Despommier of the Columbia University, Environmental Health Science Department (USA) [21]. The major strengths are discussed under the following topics:

Industrialisation of Agriculture: Industrialisation is the extensive organisation of an economy for the purpose of manufacturing. It is also optimal use of energy for maximal resource use. Industrial agriculture has till date used agricultural machinery, advanced farming practices and genetic technology to increase yield. However from a socio-economic perspective agriculture has not changed much relative to other manufacturing industry. It still needs extensive tracts of fertile land for the purpose of food, fuel or fibre production, as it did 10,000 thousand years ago. It still remains a time consuming process solely dependent on the biological constitution of the cultivated crop. Although green revolution advocated the elimination of photoperiodism of a number of crops, agriculture still largely depends on season, especially in case fruit and vegetable crops. Socio-economically this renders the farming population under or unemployed for a greater part of the year. While in industrialised nations, higher food prices, greater affordability and government subsidies mollifies this problem to some extent, in developing countries, where sustenance agriculture is a norm, this translates to poverty and vulnerability.

Vertical farming provides a paradigm shift in the way we know and do agriculture. In terms of space, abandoned urban properties, abandoned mines or even peripheries of buildings can be converted into food production centres thereby eliminating the need for expensive constructions. Moreover due to optimum use of vertical space 1 indoor acre is equivalent to 4-6 outdoor acres or more, depending upon the crop (e.g., strawberries: 1 indoor acre

= 30 outdoor acres), something that is inconceivable in case of conventional or greenhouse agriculture. This intensifies agriculture instead of extensifying it, as has been the norm. Due to provision of artificial light at the correct wavelength (380-450 nm in the violet end and 630-700 nm in the red end) for an optimal duration, crop production becomes an year round enterprise, comparable with other manufacturing industries. Moreover, through optimum and timely distribution of nutrients and regulation of CO_2 concentration, something inconceivable under normal circumstances. It also creates new employment and research opportunities. We cannot go to the moon, Mars, or beyond without first learning to farm indoors on earth. Technologies developed for VF may prove to be useful for application not only for space applications or remote research stations like in the poles, but also in refugee camps especially in flooded or earth quake affected areas where camp dwellers need to be fed for prolonged period of time.

Independence from external threats: Agriculture has always been affected by vagaries of weather. Fluctuations in temperature, water availability, photo-intensity beyond the biological requirements of the plants have persistently lead to dwindling yields. To add to the limits soil, water and air borne fungal, viral, and bacterial diseases in addition to insects, nematodes, aphids and other pests and weeds have affected the yield. These factors have always remained beyond the control of farmers and could only be prevented through costly chemicals, avoidance of high-risk high-profit crops, or purchase of crop insurance. Vertical farming systems addresses many of these problems. Like greenhouse agriculture, there is no weather-related crop failures due to droughts or floods as irrigation is artificial and controlled. Temperature and photo-intensity and duration is also artificial and optimal. Due to semi-closed system of agriculture, VF greatly reduces the incidence and facilitates prevention and timely quarantine of many infectious diseases that are acquired at the agricultural interface. Therefore, all food can be grown organically and sustainably without herbicides, pesticides, or fertilizers without compromising on the yield or soil quality.

Energy generation: While conventional agriculture receives natural light free of cost, it is still an energy intensive process. Starting from soil preparation to harvesting, energy is required to run the machinery. Fertilisers and pesticides are also derived from fossil fuels. Moreover, since production usually takes place far away from the point of consumption, energy is required for extensive post harvest processing and thereafter for refrigeration and/or transportation to the point of consumption. Vertical Farming may add energy back to the grid via methane generation from composting non-edible parts of plants and animals. Although the balance of energy required for artificial lighting, heating and cooling and that generated by bio-gas is a matter requiring further research. VF dramatically reduces fossil fuel use since there is no agricultural machinery, inorganic fertiliser involved. Although energy required for plant system support is often drawn from fossil fuels. Furthermore, since food is grown locally or closer to points of consumption, transportation is minimum, thus saving on energy and the environment.

Environment: Agriculture especially in developing and transitional economies have often been held responsible for environmental degradation, loss of rainforests like in Amazon basins or desertification and loss of ground water as in Khorezm basin. In addition the growing controversy regarding production of fuel from food crops or emission of green house gases through indiscriminate ploughing have also not served in favour of conventional agriculture. Since the publication of "Silent Spring" by Rachel Carson in 1962, ground water pollution caused by agricultural run-offs have also remained a hotly debated topic. VF returns farmland to nature, restoring ecosystem functions and services. At least high value fruits and vegetables cultivated in vertical farms can ease some pressure off agriculture by which fertile lands can solely utilised for cereal, fodder, fibre and bio-fuel production. VF can virtually eliminate agricultural run-off by recycling black water. In urban settings or desert nations VF systems may be used to convert black and grey water into potable water by collecting the water of evapo-transpiration which is one of the many functions of the greenhouse module used in remote areas and for the purpose of space explorations, where water is scarce. VF may additionally create sustainable environments for urban centres purifying the air and providing a positive psychological effect on urban populace often deprived of greenery. Like botanical gardens and parks, they can serve as the lungs of the city landscape, relieving it of smog and harmful air pollutants.

18.2.2 Weaknesses

Crops require space, light, carbon dioxide and water, everything else is required in relatively smaller quantities. In conventional agriculture we are used to getting these things for free, the ambient light, natural precipitation, growing space, nutrient delivery channels are present in nature and often taken for granted. In case of vertical farming all these need to be supplied at a cost. Therefore in order to make this viable, one has to quantify the price of these facilities and see if the crops grown in vertical farms can compete in the market with normally produced crops despite their handicap.

Space: In case of vertical farming abandoned buildings, mines even peripheries of residential or office buildings may be used to provide space for crop cultivation. This is however not free of cost. Some structures need to be built for the nutrient delivery system and platforms for plant growth along with artificial growing medium. This could be a weakness as against conventional agriculture, where special structure need not be constructed, greenhouse agriculture on the other hand has the same issue. Taking this into consideration, vertical farming is logically viable only in places where agriculture is necessary but agro-climatologically difficult to be practised in the open, like in desert nations, nations lacking plain arable land like mountainous countries. This might also be justified as a space saving approach in Mega-cities where real estate demands hinder setting up of parks and botanical gardens.

Light: The average insolation on Earth irrespective of cloud cover is around 250 W/m^2. This is for free. In vertical farming towers this has to be supplied artificially. Although it opens up the opportunity to regulate the wavelengths, intensity and photo-period to optimal levels, and can be held comparable to greenhouse agriculture, it still remains a cost that needs to be taken into consideration. The justification of incurring this extra cost lies in areas where light intensity is too low or the photo-period incompatible for crop cultivation, as in higher latitudes or where the intensity is too high for cultivating sensitive salads, fruits and vegetables, as in sub-tropical deserts.

Water: Only in case of rain-fed agriculture is water free for the field crops. Although vertical farming requires water to be pumped to greater heights and plumbing is required for water and nutrient delivery to every single plant in the culture. Although it is not a significant weakness when compared to irrigated or greenhouse agriculture, it is still an extra cost component that needs to be taken into consideration.

The Energy balance: In locations where the cost of energy required to light, heat and cool the indoor farms is significantly lower than the cost of importing food, Vertical Farms is a viable option. But elsewhere the cost of powering artificial lights will make indoor farming prohibitively expensive. Though crops growing in a glass skyscraper will get some natural sunlight during the day, it will be available only at the periphery of these structures. Without artificial lighting, crop growth will be uneven, as the plants closest to the windows are exposed to more sunlight and grow more quickly, while the ones away will be stunted and yield less.

Despite promising projections, such high-rise farms still only exist as small-scale models. Critics don't expect this to change any time soon. The main problem is light in particular, the fact that sunlight has to be replaced by LED. In order to replace all of the wheat cultivation in the US for an entire year using vertical farming, eight times the amount of electricity generated by all the power plants in the US over a single year will be required just for powering the lighting [30]. Renewable energy sources only generate about 14.3% of all power in the US [82]. Therefore, the sector would have to expanded 55-fold to create enough energy to illuminate indoor wheat crops for an entire year using renewable energy alone. However drawing from the arguments already presented above, there are places on Earth where vertical farming may be a viable option.

18.3 External analysis

The exogenous factors on which a particular enterprise has no influence upon, but can affect its performance positively or otherwise, feature in the external analysis. These are categorised under the opportunities and threats respectively.

18.3.1 Opportunities

Opportunities include those external factors and conditions which an enterprise should take note of and maximise upon in order to gain success. In this case some of the opportunities are being discussed as cases.

Consumer preference: There is an increasing demand for protein, vitamin and mineral rich food as more and more countries transition from developing to industrial nations. Despite Engel's law of declining share of food related expenditure with increasing income, there is expected to be a change in the pattern in which the people in these countries consume [60]. In particular, Cranfield et al. [19] expect reduced consumption of unprocessed bulk commodities (e.g., grain, rice and cereals) along with an increased consumption of higher valued consumer-ready products (e.g., fruit, meat and dairy products). This changing consumer preference is an external factor that might serve as an opportunity for vertical farming. Because, vertical farming is particularly efficient in producing sensitive crops of high nutritional value in harsher agro-climatic zones since it takes weather out of the equation.

Climate change and Environmental concerns: As seen in figures: 1.2.1 and 1.2.2 it is clear that places where population is growing, also happens to be places where land is shrinking in terms of arability. Vertical farming might also find opportunity in this dismal fact.

Table 18.1: Greenhouse gas emission in agriculture

(a) U.S. Greenhouse gas emission by economic sector (2005).

Sector	Percent
Electric power industry	33.5
Transportation	22.7
Industry	18.6
Agriculture	8.2
Commercial	5.9
Residential	5.2
Other	0.8

Source: [27]

(b) U.S. Agricultural greenhouse gas emission by economic sector (2005).

Source	Percent of	
	Total emissions	Agricultural emissions
Soil Management	5,0	61
Enteric fermentation	1.5	18
Manure management	0.7	9
Fossil fuel consumption	0.6	7
Other	0.3	4
Total	8.2	100

Source: [27]

The tables: 18.1a and 18.1b lends the reader a perspective on how conventional agriculture contributes to emission of greenhouse gases and therefore towards climate change. Land management, through ploughing and manuring contributes to almost 88% of the agricultural emissions in the U.S. Vertical farming, which completely rules out this measures, therefore has an advantage in this front. Global climate change therefore presents an opportunity for vertical farming to get greater social and political acceptance.

In addition to this there is an increasing controversy regarding the use of arable land for bio-fuels and the later contributing towards raising of food prices [7]. Vertical farming can relieve high yielding land, now used for fruit and vegetable cultivation, so that they may be optimally used for whatever purpose the economy deems necessary.

Race for food sovereignty: Recent decades have seen food sovereignty being sought by many nations and recommended by many think-tanks in view of the volatility of food prices. This is seen especially in geographical regions where purchasing power is high but agro-climatic factors too hostile for conventional agriculture, like in Deserts, Taigas and Tundras.

Renewable Energy: The recent developments in the field of renewable energy be it in Photovoltaics or Solar Thermovoltaics or Wind or even Pumped-storage Hydroelectricity are noteworthy as opportunities. Not only because in larger scale they might open doors for cheaper electricity but also because of their location. Since they are mostly located in areas unfit for agriculture, even a small fraction of their generating capacity might be used for the purpose of a VF.

18.3.2 Threats

Scepticism: The biggest threat to VF is scepticism from business and academia, and it is not entirely unfounded. Till date no project has practically demonstrated the viability of a VF at this scale, most exist in small research initiatives or as concept drawings by architects. Therefore it is imperative that initiation leave alone acceptance would require convincing at different levels and hence requires some serious action research. This work is a step towards removing this scepticism by showing the economic feasibility at least in the drawing board by spelling out all the parameters clearly.

Existing patents: This is a threat not to vertical farming but to DLR as such. Since there are lot of early entrants as discussed in the section §2 on page 13 DLR might face initial challenges as a market entrant. In this regard DLR will therefore have to invest in research and innovation and use its unique resources and know-how to tackle this problem head-on. While this is a unique business opportunity which has not been utilised to its optimum level, and has the potential to yield profits for DLR in terms of patent rights and consultancy fees, procrastination will not serve to its benefit. Since some resourceful organisations are already taking notice of the potential and investing heavily in this area as is seen in the case of Plantagon in Sweden.

Limited market opportunity: Market opportunity is not widespread. It is feasible to grow only high value crops for consumers with dispensable money for such products. It has no merit to flourish even in Mega-cities in resource rich nations as long as conventional agriculture can supply food cheaply. The time for such technology might not have come yet, in other words, the pressure on our resources are still not that high that such costly measures can be taken. That being said, it does not mean that we should not develop this technology for the areas where it could be deployed presently. Although this technology might not see mass production in near future, successful implementation of the technology in potential markets will definitely improve its marketability.

Price and subsidies: In 2010, the EU spent €57 billion on agricultural development, of which €39 billion was spent on direct subsidies. Agricultural and fisheries subsidies form over 40% of the EU budget [28]. The United States spent around $20 billion per year to farmers in direct subsidies as "farm income stabilization" via U.S. farm bills [81]. Although the merits or demerits of these measures may be seen from different perspectives and is debatable, from the point of vertical farming prospects, one thing is clear. These subsidies are there for the sole purpose of enabling the farmers to act competitively in a globalised world. This will definitely not serve in favour of vertical farming. Due to subsidies conventional agriculture can and will supply food at prices much lower than the real price and therefore present a tough competition for this new technology, where energy costs are a big concern. Therefore, the way out lies in marketing this solution in areas where such subsidies are not present– this is increasingly difficult in a globalised world or avoid competition with conventional agriculture by producing niche high value products.

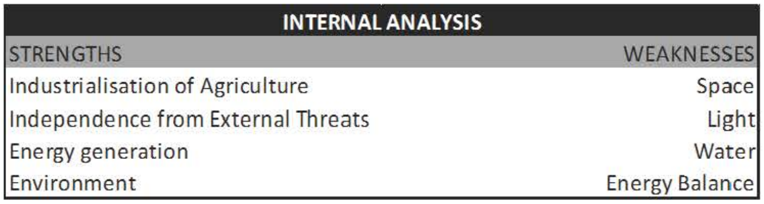
Moreover, as we see in the previous part, the cost of producing a unit of biomass in vertical farm is prohibitively high, as compare to traditional agriculture. This is not only due to high power demand, but also due to expensive machinery required.

18.4 Qualitative SWOT Analysis

In the Figure: 18.4.1, the internal and external analysis have been tabulated. On the basis of this one can go forward to the next step for the qualitative analysis. Based on the tabulated factors a SWOT matrix can be created. It connects different arguments with each other. The process of finding relationships between the different findings is a subject of personal evaluation, so other relations can be found and also justified.

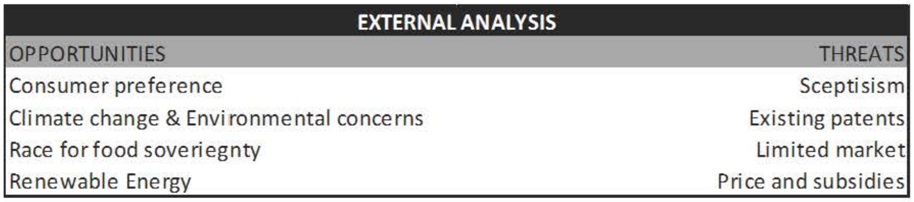
Figure 18.4.1: SWOT Analysis

(a) Internal Analysis



INTERNAL ANALYSIS	
STRENGTHS	WEAKNESSES
Industrialisation of Agriculture	Space
Independence from External Threats	Light
Energy generation	Water
Environment	Energy Balance

(b) External Analysis



EXTERNAL ANALYSIS	
OPPORTUNITIES	THREATS
Consumer preference	Sceptisism
Climate change & Environmental concerns	Existing patents
Race for food soveriegnty	Limited market
Renewable Energy	Price and subsidies

Figure 18.4.2: The SWOT Matrix

SWOT	STRENGTHS	WEAKNESSES
OPPORTUNITIES	Use strengths to maximize opportunities	Minimize weaknesses by taking advantage of opportunities
THREATS	Use strengths to minimize threats	Minimize weaknesses and avoid threats

18.4.1 The First Quadrant

In the first quadrant the strength layer has an intersection with the opportunity layer. The point of convergence where the strength of the enterprise addresses some opportunities is with regard to the Environment. Climate change, increasing CO_2 emissions caused by mechanised agriculture as well as transportation and related storage of food are some of the grave issues that can be addressed by VF. In addition to that increasing urbanisation and thereby increasing urban wastes needs environment friendly treatment, which VF offers.

Race for food sovereignty is another major issue that can be addressed since VF can grow food in places otherwise hostile for agriculture. This particular topic is being discussed in detailed with an example of "Saudi Arabian Agriculture".

18.4.1.1 Agriculture in Deserts

Figure 18.4.3: Agriculture in desert

Source: [43]

Deserts can be described as areas where more water is lost by evapo-transpiration than falls as precipitation. With an average rainfall of only 70-100 millimetres a year conventional farming in Saudi Arabia was out of question. Until recently, when Saudi Arabia became sufficiently oil-rich to purchase modern equipment and reclaim the land, large volumes of groundwater from mostly non-renewable aquifers began to be extracted [26]. The Saudi desert irrigation projects were an aberration in the history of desert agriculture. The population in the Arabian Desert has always been limited to a size that could be supported from mainly shallow wells and scant oasis waters. In 1980, the Saudi population was estimated at 9.8 million. The population's three fold increase by 2010 to 27.44 million has been phenomenal [84]. The rapid growth partly resulted from the October 1973 quadrupling of oil prices and the consequent expansion of the Saudi economy and agriculture. Although it is an egg-hen conundrum, weather agriculture spurred this growth or the growth spurred agriculture in desert, one thing is clear, within 12 years, between 1980 and 1992, wheat production grew to 4.1 million tons in 1992. To achieve this enormous growth, wheat-producing areas were increased by 857,000 hectares from 67,000 hectares in 1980 to 924,000 hectares in 1992 (FAOSTAT). The experience proved that investing to import the expertise and the machinery to extract mammoth volumes of water could make agriculture in desert possible, but is not sustainable [26]. But it also proves that these countries are ready to subsidise and spend that extra money to attain food sovereignty. Vertical farming which undoubtedly is more sustainable than the form of agriculture hitherto practised, might find a market in these countries.

The financial cost: For the period between 1984 and 2000, an estimated cost of Saudi agricultural development is about $85 billion, representing 18% of the country's $485 billion in revenues from oil exports during the period. This excludes costs arising from abandoning the newly reclaimed and irrigated lands plus four unquantified government subsidies. The first being the government's price support to electricity and fuel, which benefited the farmers. The second is the value of the concessionary borrowing terms on a total of $9 billion granted to 394,000 loans by the Saudi Agricultural Bank by 2000 [61, 26]. The third is the value of 1.67 million hectares of government land given away between 1980 and 1992 under the 1968 Regulation for Fallow Land distribution, and which was used in farming [26]. The fourth is the cost of the bureaucracy that the Saudi government had to employ in order to administer the new agricultural schemes. This huge investment produced wheat at an average cost of more than US$500 per ton [25]. During the same period, the international market price for wheat averaged about $120 per ton (FAOSTAT).

The resource cost: Between 1980 and 1999, 300 billion m^3, was used in Saudi Arabian agricultural. About 200 billion m^3 of the water thus used is regarded as non-renewable, according to estimates by the Ministry of Agriculture and Water (MAW) [25]. The annual water requirement for Saudi agriculture was 17 billion m^3 in 2005 that means an average of 15,760 cubic meters per hectare [62].

The persistent rise in the per hectare use of water was due to the fact that most of the water was used in practices that usually require more water than cereals (such as animals, animal products, fruits, and alfalfa) [26]. Just to put it to perspective, 1,000 m^3 water is required to produce a ton of wheat and 16,000 m^3 to produce a ton of beef and 5000 m^3 is needed to produce a ton of chicken in Saudi Arabia [26].

The volume of water extraction from non-renewable aquifers, according to the Saudi Ministry of Agriculture and Water, reached a peak of slightly more than 14 billion m^3 in 1993 and 1994 [26]. From Hubbert's theory, the period starting 1993-1994 might signify the midpoint in the volume of Saudi non-renewable water reserves [40, 26].

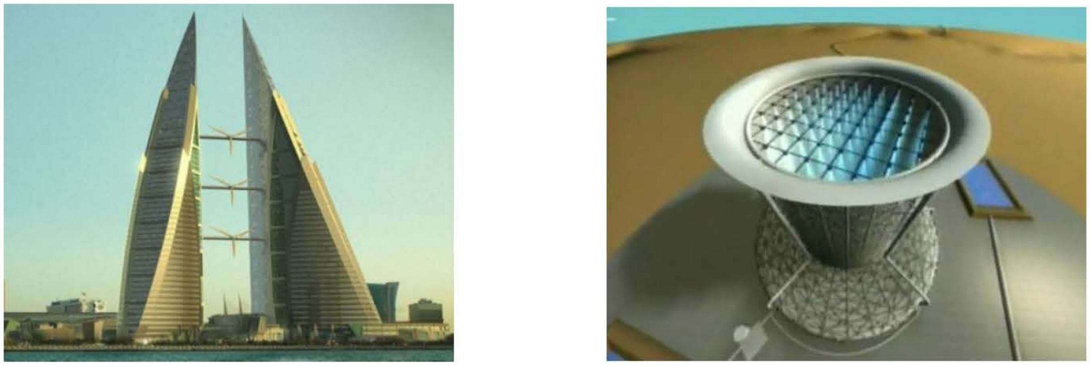
According to Saudi Ministry of Agriculture and Water, the aggregate volume of water extracted from the non-renewable aquifers between 1980 and 1994 was 140 billion m^3 [61]. Hubbert's theory suggests that the volume of Saudi non-renewable water resource was likely to be around 280 billion m^3 and the remaining volume of water after peak was 140 billion m^3. Therefore, if the average extraction remains at 10 billion cubic meters per annum, then the volume would last 14 years [26]. In addition to already dried aquifers, unmonitored use of inorganic fertilizers and pesticides, have rendered most aquifers brackish. Therefore technologies with a promise of judicious use of water as well as food sovereignty should be more than welcome despite requirement of higher financial investments.

This example merely shows the willingness the governments of these Desert and Taiga regions have to attain food sovereignty. VF with its given properties are definitely a candidate worth marketing to them. This is an area where the strength could be maximised to bank on the opportunities.

18.4.2 The Second Quadrant

In the second quadrant the weakness layer has an intersection with the opportunity layer. The point where one can minimise weakness by banking on the opportunities is energy. Renewable energy is a area rapidly making strides around the World (see Figure: 18.4.4[1]). Energy balance of the VF is on the other hand extremely skewed. Development of integrated projects where renewable power stations are coupled with VF will not only increase their marketability but also subsidise their costs mutually. German industry as well as DLR has immense expertise and know-how in this area. Development of such projects will give them a clear upper hand against their competitors.

Figure 18.4.4: Buildings generating renewable energy



The Bahrain World Trade Center with 3 Wind Turbines

1,200 m high Energy Tower coming up in Arizona could be home for Vertical Farms

A vertical farm as per the system analysis presented in this paper, requires a net total of 3.5 GWh of electricity a year. Monumental as it seems, this is less than the amount of electrical energy generated by a power station of 0.5 MW installed capacity in a year running at full capacity. A wind turbine of 80 m length, for example has an generating capacity of 2.5 MW. The following example of a DLR pioneered solar power station shows where a VF could possible be integrated.

---

[1] Source: http://www.davidtan.org/ and http://www.cleanwindenergytower.com/ respectively

18.4.2.1 Solar thermal tower:

The PS10 Solar Power Plant (Figure 18.4.5), is Europe's first commercial concentrating solar power tower operating near Seville, in Andalusia, Spain. The 11 megawatt solar power tower produces electricity with 624 large movable mirrors called heliostats [68]. It took four years to build covering an area of 55 hectares and so far cost €35 million. PS10 produces about 23,400 MWh per year, for which it receives €0,27 per kWh under its power purchase agreement. DLR made major technological contribution towards its construction and operationalisation.

Figure 18.4.5: The PS10 Solar Power Plant

Source: [68]

The DLR Institute of Technical Thermodynamics has been working for 30 years on research and development of solar-thermal power plants. With more than 80 scientists (spread across the Stuttgart, Cologne and Almería/Spain locations), the institute is one of the world's leading research facilities in this field.

In 2009, the solar thermal experimental and demonstration power plant in Jülich was made operational. The technology for the core of the facility, the receiver, was developed and patented by the German Aerospace Center (DLR). DLR, together with the Jülich Solar Institute, provided scientific guidance and support for the planning, design and operation of the power plant. 2,153 movable mirrors (heliostats) with a total area of almost 18,000 square meters, arranged over an area of around eight hectares concentrate the solar radiation on a receiver that is around 22 square meters in size, installed at the top of a 60-metre tower. The steam generated through this heat drives a turbine, which produces power via a generator. The power plant will supply 1.5 megawatts when operated at its rated capacity [23].

The list is long but the most significant of all cases is that of DESERTEC. Cheap, safe and environmentally friendly electricity from concentrating solar power systems could meet about 15% of European power needs by 2050. DLR has supplied the scientific foundation for the DESERTEC project [24]. DESERTEC will use solar-thermal power plants in Earth's sun belt to generate climate-friendly electricity for Europe, the Middle East and North Africa (MENA). The 'MED-CSP', 'AQUA-CSP' and 'TRANS-CSP' studies conducted by DLR concluded that solar-thermal power plants could supply sufficient power and desalinated water to meet the growing demand of MENA countries as well as Europe, while using less than 0.3% of the MENA desert area. The MED-CSP study focuses on the sustainable supply of electricity in MENA countries while AQUA-CSP analyses the drinking water supply. Which all in all solves the most pressing challenge faced by vertical farming, namely, energy and water in non-arable regions [24].

This is an unique selling point for DLR, which gives it an advantageous position ahead of all its competitors. By combining its know how in the field of energy generation from renewable sources as well as producing water as a bi-product of this process, DLR can develop and market self contained vertical farming systems, which not only addresses the food production issues but takes care of its water and energy needs in areas where agriculture is virtually impossible.

18.4.3 The Third Quadrant

The third quadrant shows the intersection of strength and threat layer. This quadrant indicates a possible threat to the enterprise or the product, but it also shows a possible strength of the enterprise in order to prevent this particular threat. A list of possible combinations in this quadrant includes the one already discussed above, namely the integration of renewable energy stations with VF, which would give the German Industry an advantage over the existing patents. In addition to that is the environmental and ecological services provided by VF that could open new markets in face of market limitations. But above all is its performance against traditional agriculture that could turn the balance in its favour.

18.4.3.1 Comparison with traditional agriculture

So how does a VF compare to a traditional farm? Plant cultivation in field (climatic influences) and in closed environment (protected cultivation) creates different amounts of yield. There is an increase in yield of all crops in the VF due to a number of factors discussed in the SWOT analysis.

By the application of vertical frames and multiple stacks, the basic ground area of the building (2500 m^2) is increased 37 times to an expanded plant area to a total of 92,718 m^2, comprising of a total of 116 stacks through 25 floors. Although the ground area is reduced by a factor of 0.64 (floor area/ground area) and the floor area further by a factor of 0.57 (growth area ratio = effective floor area/floor area) leading to a total factor reduction of 0.37 due to structural considerations, resulting in an effective floor area of only 918 m^2 (refer to Table 7.1). This results in a total production of 3,573.41 tons of edible plant biomass. If field crops were grown in an area as big as the total stack area of the tower, and harvested as many times, traditional agriculture would have produced 1,684.94 tons, which means due to closed environment and controlled lighting vertical farming is twice as good. However, for this only 2500 $m^2$is being used, so if we grew all those crops proportionately on the same 2500 m^2 and harvested once (as in traditional agriculture) the area allocation would look like column 5, and yield like column 6 of Table 18.2. This means multiplication of the yields by a factor of 516! Which makes vertical farming a viable candidate, at least theoretically for our race to multiplying the food production by 100% by 2050 [72, 36].

Such performance coupled with proper research and integration of additional services (refer

Table 18.2: A comparison to traditional agriculture

CROPS	FIELD YIELD (TONS PER HA)	YIELD IN AREA AS IN V-F (TONS)	FACTOR INCREASE DUE TO TECH	PROPORTIONATE AREA (m^2)	PROPORTIONATE YIELD ON 2500 m^2 (TONS)	FACTOR INCREASE DUE TO V-F AND TECH
CARROTS	30.00	107.22	1.92	198.02	0.59	346.90
RADISH	15.00	100.52	1.53	123.76	0.19	828.70
POTATOES	28.00	71.08	5.39	247.52	0.69	552.32
TOMATOES	45.00	212.87	3.44	297.03	1.34	547.76
PEPPER	30.00	94.61	4.42	198.02	0.59	704.28
STRAWBERRY	30.00	70.96	2.31	148.51	0.45	368.26
PEAS	6.00	32.17	1.57	297.03	0.18	282.79
CABBAGE	50.00	197.10	1.35	247.52	1.24	215.00
LETTUCE	25.00	718.01	1.47	594.06	1.49	709.28
SPINACH	12.00	80.42	1.82	148.51	0.18	820.33
TOTAL		**1684.94**	**2**	**2500**	**6.93**	**516**

to section of "Further Research") could bring down costs and boost its attractiveness even in places where marketability is currently out of question.

18.4.4 The Fourth Quadrant

The fourth quadrant, which is also called the dead quadrant, shows the intersection between the weakness layer and the threat layer. In this quadrant the enterprise has to face a threat, but can only oppose a weakness in this field. Therefore, the strategy is to minimise the weakness and avoid the threats. This quadrant leads to a strategy elaborated in the section on Further Research, cause only through investigating possible methods of optimising space, light, water and energy requirement and maximising yield can the weaknesses be minimised. In addition this strategy would also help avoid threats arising from general scepticism regarding the viability of this project as well as creation of market opportunities.

The threat of existing patents is one for German industry, if big firms start taking interest and are convinced about its business potential, the threat is minor. Since most of the organisations engaged in this business are small research groups or firms classical M&A strategy would serve the cause.

As far as price and subsidies are concerned, once the Governments are convinced of the viability and positive attributes of VF this threat also stands a minimal chance. Besides being a carbon neutral enterprise, there is a possibility of carbon trading, which will offset the high cost of production to some extent. In addition to that, the price is high due to the high costs of equipments as well as the power costs. While power costs could be tackled only through research into energy efficient production system, the equipment costs are expected to go down once the trend catches up and serial production of these equipmentation starts. For that matter it is important to throw light on the market potential of this technology.

All in all, the call of the day is to start integrated research projects to investigate the questions that have been identified by this research and kept open ended.

Chapter 19

Market Potential

Having discussed the limitations of market potential with regards to areas where traditional agriculture can supply cheap produce or where the purchasing power of consumers are not high enough, this chapter discusses the potential of marketing this technology notwithstanding the limitations and scepticism. Presently the biggest markets for this technology according to the above analysis, is in Desert regions, Taiga region and Mega-cities. What it means in terms of numbers have been discussed in the subsequent sub-chapters. The statistics refer to only those countries or cities, where the GDP per capita is USD 20,000[1] or more. This is selected as a cut off mark as purchasing power of the consumers is the most important factor for assessing market potential, beside the urge for food sovereignty and incompatibility of agro-climatic factors for food production.

---

[1] The data presented are a rough estimates based on the projected figures in Wikipedia (http://en.wikipedia.org/wiki/List_of_cities_by_GDP) and CIA- The World Factbook (https://www.cia.gov/library/publications/the-world-factbook/)

19.1 Desert Region

Table 19.1: Statistics of Middle Eastern Nations

Country	GDP per Capita	Population	Market potential
Qatar	$102,700	1,853,563	18
United Arab Emirates	$42,000	8,264,070	82
Kuwait	$40,700	3,566,437	35
Israel	$31,000	7,879,500	78
Oman	$23,900	2,773,479	27
Bahrain	$21,200	1,234,571	12
Saudi Arabia	$20,400	27,136,977	271

By desert regions Middle East and North African (MENA) countries have been referred to. Although there are many other countries like Australia, and the US which have substantial stretches of land that fall under the category of desert, due to other fertile tracts, these nations are not resource constrained and enjoy food sufficiency. The nations shown in the Table: 19.1, have been selected because they are resource constrained, do not enjoy food sovereignty, but can financially afford to do so (as shown by the GDP per capita figure being above USD 20,000).

If it is assumed that only 100g of VF produce is consumed per head per day, the design presented in this thesis, can feed around 100,000 people round the year. Based on this figure the market potential has been calculated, simply as a quotient of the present population and the supply potential of a VF (100,000 people). This is probably not the number of farms that would be built, but it gives us a rough idea of how many could be build and what potential lies ahead for this technology. If we go for the short run, just for pilot projects, one could safely assume two VF to be built in every country totalling to a figure of 14 towers, until the trend catches on and series production of this technology commences.

It is worth noting that the system assumption in case of deserts would be completely different. Besides, due to high potential of harvesting solar energy and distilling sea water, the cost of production could be drastically reduced, giving these nations an upper hand in food production potential formerly unthinkable of. Although the systems have to be closed with water recycling capacity.

19.2 Taiga Region

Table 19.2: Statistics of Nordic Nations

Country	GDP per Capita	Population	Market potential
Denmark	$37,151	5,543,453	55
Norway	$53,470	5,003,000	50
Sweden	$40,393	9,415,295	94
Finland	$49,349	5,410,233	54
Iceland	$38,060	320,060	3
Greenland	$37,517	56,615	1

The nations lying in the Taiga regions also have comparable situation. Although other countries like Russia and Canada lie in these region, they have other fertile tracts that offsets their food dependency as a nation and hence they were left from the analysis. The Nordic countries have inconducive conditions for agriculture, high purchasing power and abundance of renewable energy in the form of hydro-electric or off-shore wind power. In addition to that they strive for food sufficiency which makes them a good market for VF technology. This is also seen in the projects been developed in Sweden [58]. Table: 19.2 gives us an overview of the same. Again, at limits one could construct as many VF as shown in the last column although that is unlikely. However, one could safely assume that for pilot purposes, even if two VF are constructed per nation, 12 VF could come up in the short term. In terms of system design, water recycling might be left out of the equation thereby bringing down the operational cost drastically. Moreover they will only require heating which could be channelised from residual heat form industries, or geothermal heat, which is so ubiquitous in Iceland. This would help bring down the power costs of the system and lead to lower cost of production.

19.3 Mega-cities

Table 19.3: Statistics of European Mega-cities

City	GDP per Capita	Population	Market potential
London	$75,330	7,500,000	75
Paris	$50,900	11,090,000	110
Madrid	$39,600	5,800,000	58
Barcelona	$35,600	4,970,000	49
Berlin	$28,500	4,970,000	49

Table 19.4: Statistics of North American Mega-cities

City	GDP per Capita	Population	Market potential
Washington, D.C.	$76,200	5,580,000	55
New York City	$67,700	18,900,000	189
Houston	$64,600	5,950,000	59
Dallas	$58,700	6,370,000	63
Philadelphia	$58,200	5,960,000	59
Los Angeles	$57,500	12,820,000	128
Chicago	$56,300	9,460,000	94
Atlanta	$51,700	5,270,000	52

Table 19.5: Statistics of Asian Mega-cities

City	GDP per Capita	Population	Market potential
Hong Kong	$45,268	7,069,000	70
Singapore	$44,449	4,837,000	48
Tokyo	$40,334	36,669,000	366
Osaka	$36,782	11,337,000	113
Seoul	$29,776	9,773,000	97

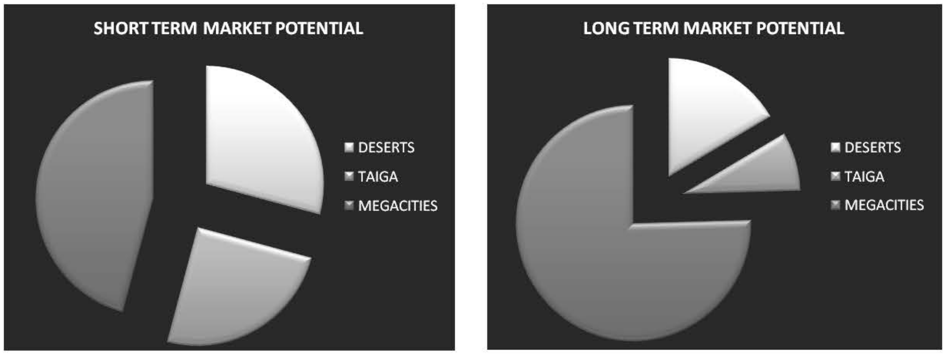
Table 19.6: Statistics of South American Mega-cities

City	GDP per Capita	Population	Market potential
Buenos Aires	$27,689	13,074,000	130
Santiago	$20,161	5,952,000	59
Mexico City	$20,041	19,460,000	194

From Tables: 19.3 through 19.6 the market potential in Mega-cities have been tabulated. The criteria for consideration in this analysis being population of around 5 million and per capita GDP of above USD 20,000. Under this criteria, one gets 5 cities in Europe, 8 in North America, 5 in Asia and 3 in South America. Since this is an expensive venture it is conservative to take such estimates. Piloting in the initial years will be done not only for food production purposes but also to add prestige to the city and provide ecological services, before VF can fully demonstrate its worth. These motives can only expected in comparatively rich cities with high level of environmental consciousness. In terms of system design, these VF will require everything conceptualised in this study from water recycling to external power input, in addition it can incorporate systems for grey water purification. However, the prime real estate may be used for additional purposes to house offices, hotels or botanical gardens in the periphery thus bringing down the capital expenditure required solely for the VF construction. Although the full market potential is high, assuming one VF per city, we are still looking at around 21 VF that could come up as pilot projects in mega-cities around the world.

19.4 In a nut-shell

Figure 19.4.1: Market share



(a) Pilot farms

(b) Full realisable potential

For a company interested in investing in this new technology, what does the above analysis mean in a nut-shell? The answer lies in Figure: 19.4.1. Considering the countries in the desert and Taiga regions, and the mega-cities, there is a potential of setting up around 2900 VF.

Although this projection looks utopian, mass production will bring down costs, research will make production cheaper, as a result of which the market potential will extend to cities and countries not envisaged in this analysis.

However, for the starting point, one could just look at the number of VF that could be built as pilot projects. Assuming two for each country and one for each mega-city, a total of 47 VF could be build in the short term.

The market share shown in Figure: 19.4.1 shows the short and long term shares. This allows the company to decide what type of system needs to be emphasised on. Both for the short and long term one can project that the greatest potential lies in the systems developed for mega-cities. This is followed by desert regions. With an increasing threat of desertification caused by climate change, this segment is also going to retain its importance. Nordic countries has the smallest share both in short and long term. Moreover, this market once served will acquire saturation, provided the costs do not come down drastically. In that case similar technology will find home in other places of the Taiga regions and could be customised for northern cities mirroring similar conditions of prolonged winter.

Hence, one could conclude that there is considerable market potential for this technology and therefore pilots should be initiated to tap these markets.

Part V

Paradise Gained

Chapter 20

Summary and Discussions

In order to do a market analysis for a technology like VF, which is still in concept phase, one needs to first detail the system, estimate the cost of production and then assess the market potential. In this paper, a system design for Vertical Farm has been presented with 37 floors totalling a height of 167.5 m. Five floors are underground, housing the 3 floors of Aquacultural and 2 of Waste Management sub-systems and 32 are above ground comprising of the 25 floors for Agricultural and 2 for Food Processing sub-systems among others (refer to Figure: 6.0.1). The building occupies a land area of 0.25 ha, a footprint area of 1,936 m^2 and floor area of 1,600 m^2 , giving it an aspect ratio of 3.81. This area is multiplied to 9.27 ha for plant growth due to multiple stacking and to an equivalent of 68 ha due to multiple harvest potential.

The building costs € 111.5 million and houses equipment worth € 90 million assumed to last for 30 years. It requires 80 million litres of water per year, most of which is recycled requiring only a fraction of that from external sources (since about 4000 l leave the system as sold plant and animal matter). The VF takes in 10,000 l of nutrients, sequesters around 868 tons of CO_2, and saves many more due to carbon neutral production and supply chain. However, it also needs roughly 3.5 GWh of power at € 5.3 million and produces 3,573 tons of fruits and vegetables and 137 tons of tilapia fillet. The crop production alone is roughly

516 times the yield expected from growing these vegetables in an area of 0.25 ha with the given proportion. Bi-products are mainly 2,443 tons of biological waste yielding around 3 million litres of bio-gas and recycled nutrients in addition to slurry which can be used as farm manure. Such a system can produce fruits, vegetables and fish at an average cost lying between € 3.50 and € 4.00.

Market for such a technology is mainly in resource constrained nations and mega-cities with substantially high purchasing power. Even then, such high cost of production might be a prohibitive factor. In order to bring that down, thorough research for more efficient production techniques in addition to integration and customisation of these systems with other enterprises are required. Mass production of the equipments and use of this structure for additional business and/or economic purposes will bring down the costs and increase its appeal.

20.1 Further research

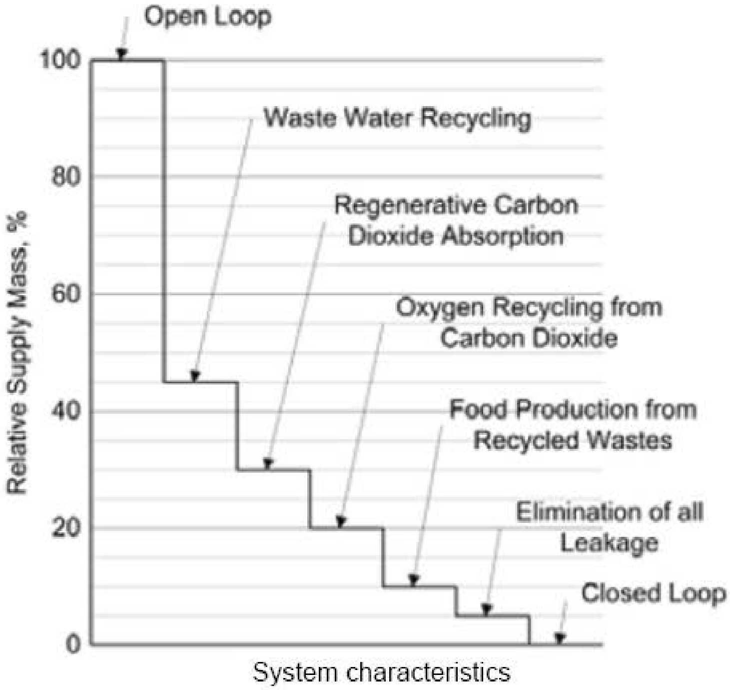
The intent of this research was to investigate whether the concept of vertical farms– which have been implemented in various forms around the world is really feasible financially and economically. And if so, will this technology be marketable and where? A prototype has been planned and discussed, and a cost analysis developed on its basis. However, in the planning phase a number of open ended issued have been discovered which is not answerable through a brain storming session, without proper experimentation. There are simply too many known and unknown unknowns. For that matter, this chapter is devoted to bring forward a couple of issues that need to be researched, as a next step now that we know this concept to be realisable. The research needs are henceforth discussed under the designated paragraphs.

The System: As could be determined from the system breakdown in Table 5.1, the Vertical Farm designed during this CEF-study will produce edible biomass through a combination of crop cultivation and fish farming.

1. Other options could have been to focus entirely on crop cultivation, to combine crop cultivation with poultry or pig farming, or even to combine all three disciplines: crop cultivation, farm animal production and fish farming.

2. The decision to do crop cultivation and fish farming in the Vertical Farm follows from a more fundamental trade-off between open loop and closed loop biomass production. In an open loop there is limited recycling and re-use of resources, whereas a closed loop system will attempt to recover resources when possible. Figure 20.1.1 gives an indication of the savings which can be gained in resource supply mass by moving from an open to a closed loop system.

Figure 20.1.1: Savings in relative supply mass of closed loop versus open loop systems



3. The trade-off between open loop and closed loop is based on the relative complexity and the potential cost savings. For the CEF-study detailed in this report it was decided to look into a closed loop system.

4. The decision to combine crop cultivation with fish farming followed from the decision to go for a closed loop system. Inedible biomass resulting from the crop cultivation is used as feed for the fish, while the waste produced by the fish can be used as a source of nutrients for the crops.

5. The trade-off between fish and farm animals was eventually won by fish, due to the relative simplicity of fish farming compared to farm animal production.

6. A different aspect of the closed loop Vertical Farm system is the Waste Management system. In an open loop system, the waste produced as a by-product of Vertical Farm operations would most likely be sold to farmers for composting, or else it would be removed for processing (at some cost) by a waste processing company. In this case, there would be no real need for a separate Waste Management System within the Vertical Farm system.

7. In the closed loop system, however, the waste produced by the crops and fish is used, to the fullest extent possible, for nutrient extraction, as well as power and heating.

8. Other important decisions which needed to be made before the start of the CEF-study were trade-offs between mono-crop and multi-crop production and natural versus artificial lighting, since these decisions have significant impact on the eventual design of the Vertical Farm and hence its economic feasibility.

9. Mono-crop production would consist of the Vertical Farm only producing one type of crop. By careful selection of this crop species, it would be possible to increase the total crop cultivation area of the Vertical Farm, as well as the edible biomass production, compared with the multi-crop production scenario. The complexity of the design would be lower as well, since the same conditions (e.g. lighting, nutrient solution) can be used on every plant cultivation floor.

10. On the other hand, the multi-crop production strategy, which would have the Vertical

Farm produce several types of crop, would be better suited to meeting the dietary needs of a population. It is precisely this reason which led to the decision to produce multiple crop species within the Vertical Farm.

11. Finally, a trade-off between natural and artificial illumination was carried out. The main factors were the potential energy, and hence cost, savings which might be achieved by using natural lighting for the crop cultivation system on the one hand, and the ability to control and optimize the lighting conditions with artificial lighting on the other hand.
12. Eventually, it was decided to use only artificial lighting in the Vertical Farm. This decision was made based on several reasons, such as the ability to specifically tailor the lighting spectrum to suit the needs of each crop, but also on the fact that no location was selected for the Vertical Farm. Since an analysis of crop cultivation with natural lighting would depend heavily on the local lighting conditions, it would require selection of a specific location. This would also mean that the economic picture of the Vertical Farm would vary (significantly) depending on the selected location for the Vertical Farm.
13. While it was unavoidable to base certain cost data for some of the cost estimations which were done as part of the CEF-study on specific locations, it was decided to make the overall design as widely applicable as possible. The design and the resulting economic picture should be (nearly) the same regardless of the Vertical Farm being in Berlin or Tokyo.

The Building: Now that is has been demonstrated that even a 37 story high building in Berlin with 30 years of life can be devoted solely to the purpose of crop cultivation, a couple of questions might be posed.

1. Urban Location: If the structure is in the middle of an urban agglomerate, it could be made to serve multiple purposes. Being in prime real estate, its periphery could be

transformed for office or residential purposes, giving enough ambient light and scenic view to each and every property. Conversely the periphery could be made to house Eco-services like botanical or zoological gardens. Such complementary developments will definitely bring up the building costs, but would also reduce the capital expenditure required solely for the VF enterprise.

2. Rural Location: On the other hand, if an action research is planned in a rural setting, solely for food production, the real estate costs will be low. In addition to that there might not be need for floors at all since the crops could be grown in a vertical tower only with intermittent service floors. It could also be coupled with Wind Farms or Photovoltaic/Solar-Thermovoltaic Power Stations, drastically cutting down the power costs.

The cost of the building, its requisite structural parameters as well as the servicing and transport equipmentation and power requirements are serious research questions that could be answered only through action research.

Agricultural System: This work draws the concepts heavily from space research, since such research has hardly been done on terrestrial conditions and if so, they hardly exist in public domain in practical form. The question was, if food can be grown for Astronauts in modules constrained by all possible resources ubiquitous on Earth, space, mass, power availability to name a few, could it be done for people on a plentiful Planet like Earth. We see that theoretically it could work. We need to find how to do it optimally.
Even in the field of agronomy there are quite a few questions that need investigation.

1. We know aeroponics increases yield. So does elevated levels of CO_2, question is to what factor do they increase yield when applied in conjunction? What are the optimal levels of nutrient and CO_2 in a VF?

2. Can the plants absorb CO_2 from industries? How do we technically design such a

system? How do we market it as a method of carbon sequestration and sell carbon credits for additional income?

3. Further to the above issue, such a system is not only carbon neutral, but also saves tons of CO_2 emissions yearly, through saving on transportation, storage and preservation, not to mention simply by absorbing about 900 tons of carbon a year, over a area of 2500 m^2 (refer to Table: 11.1). How to price such an Eco-service?

These above questions open a entirely new area of research for Agricultural Economists, cause vertical farming in this form holds the promise of completely changing agriculture the way we know it.

Animal farming: For the purpose of integrated or separate production of animal protein, some topics have been left open during the study. Further investigations are necessary in the following points:

1. Optimal species or other alternatives
    - The study has focused on Tilapia fish but the drawbacks of these fish (Low Omega-3 and feed requirements) could possibly make other options more viable
    - In the future it might turn out that insect keeping might be even more efficient, the problem though is that entomophagy is poorly accepted within western nations.
    - Rearing cattle, hogs or poultry in the peripheries is also worth a look.
    - New techniques such as in-vitro meat production might be an animal friendly alternative for VF production.
    - Growing mushrooms actually requires the same growing conditions as the environmental requirements for Tilapia.
    - Because of this, Mushrooms might be a very interesting addition to the VF. Besides the fact that the mushrooms could be sold for consumption, their protein rich waste is very applicable as Tilapia feed.

2. Reconfiguration of layout: The layout of the aquaria could be redesigned due to the consumption of space and also for ideal work processes. In addition, the tank size could be optimized to increase production.

3. Mass balance of within the aquaculture system: Tilapia can be fed with plant-waste, leftover food and even faeces (although regulation in some countries does not permit this). However, the mass balance of waste disposal and nutrient production within the VF needs to be optimized as more and more detailed designs become available.

4. Research on environmental requirements of fish: Tilapia requires a well-balanced environment which needs to be closely monitored in order to optimize production and prevent premature deaths.

5. Growth requirements for Tilapia: Exact optimum growth requirements have the possibility to maximize Tilapia production.

6. Genetic engineering or Cross-breeding: Genetic engineering or cross-breeding provides the possibility to increase Tilapia grow rate, increase environmental resistance and Omega-3 fatty percentage.

Labour requirement: Working hours of the machines and workers depend on the harvested food and fish per day. On some days there will be less food and fish for processing, while on other days there will be hectic schedules. This means that the machines and workers will not work constantly for the same time every day, the optimal labour requirement as well as the production plan needs to be worked out. Additionally, the level of automation and mechanisation needs in-depth research since labour cost is the second biggest cost head and have a big influence on the balance sheet. These are issues which are beyond the scope of a Concurrent Engineering Study and hence call for action research.

Waste Management: Further investigations are necessary in the following areas:

1. Evaluation of AD Processes: there are six well-investigated digester processes each with pros and cons. In order to obtain maximum methane production, an evaluation of these processes can be made.

2. Residue Waste Composition: the composition of residue substrate from the AD process is not discussed in detail. Its reuse as nutrients for the farming system needs to be researched in-depth.

3. Can the plants be effectively used for grey water purification in a city, as in a space ship? How? And if so how could we use this water for irrigating the plants?

4. Crop residue is very useful to generate soil organic matter and farmers use it worldwide to enhance carbon and nitrogen content of the soil. However, Anaerobic Digestion is a proven technology for municipal waste, waste-water and sludge. It can be further evaluated whether to use AD is economical for VF or is it better to sell it directly to farmers as green manure?

The aim of the Waste Management System is to utilize waste in the VF as a resource. It is observed that with AD of waste, VF has the potential to generate methane yield of $60m^3/$ton of bio-waste. This may also generate energy of 4.9 MWh. How to maximise this yield, how to use the affluent slurry, should be practically investigated.

Power and lighting: Several LED panels for plant growth exist. Due to the high amount of panels required for the proposed VF concept:

1. An innovative panel design specialized on the requirements of vertical farming is feasible and should be investigated.

2. Besides LED lighting, indirect natural lighting feeding fibre optic cables for the light distribution can be considered for the lighting system. However, the required collector area for the illumination of 93,000 m^2 is huge and the development and building costs

have to be compared with the cost of LED lighting. Nevertheless, a hybrid design using indirect natural and electrical lighting for the illumination of the cultivated plants would be a feasible option.

3. The power demand for Environmental Regulation is completely a grey area and needs to be thoroughly researched. This can be done only in real world situation, by actually building a vertical farming tower since all existing literature pertain to space applications.

With regards to the overall power demand and cost thereof, vertical farms score dismally against traditional agriculture, where lighting, environmental control and irrigation is mostly natural. It is also no wonder that power cost is the largest head in this balance sheet. In order to address this, vertical farms may well be integrated with sources of renewable energy to bring down this cost. This plan requires additional research in terms of engineering and economics and in view of the comparative facts already presented is definitely a feasible option.

20.2 Conclusion

A billion go hungry, food prices are volatile and in low income countries, this leads more into starvation and malnutrition. Despite this, as of 2011, 1.3 billion tons of global food production is lost or wasted annually [37]. This loss takes place during storage, transportation, packaging, damage during production to name a few causes. All of these factors have to do with how we do agriculture and how we deliver this to the centres of consumption. If food is grown close to the centres of demand, under controlled environment, all of this could be avoided to some extent. Growing urbanisation also points at the same direction, whereby food grown in cities can be consumed locally with minimal transport and loss.

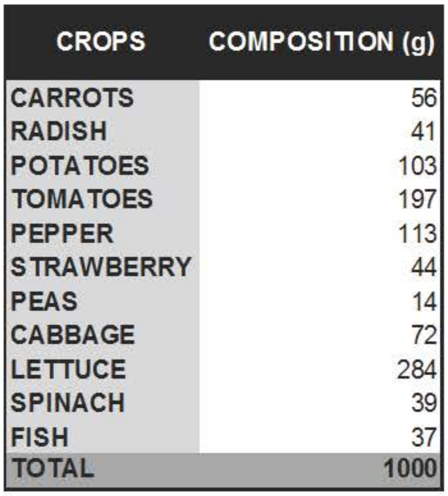
India and China are growing in number as well as purchasing power. This means a shift in consumer preference from carbohydrate rich to protein and vitamin rich diets. Growing them in traditional methods are putting enormous pressure on our already scarce resources. Poorer nations on the other hand are demanding cheap food at stable prices, one that could be easily grown traditionally. It is time a debate similar to food v/s bio-fuel must start regarding how much land should be dedicated to high value crops that could otherwise be used to grow cereals, pulses and other crops.

Climate change and desertification are worsening the situation. Changing pattern of weather is making planning for crop cultivation increasingly uncertain. More and more land mass is getting engulfed in desert like agro-climatic conditions, rendering them very difficult to cultivate. On the other hand, we need to double our food production by 2050. Simple logic dictates that we have to reclaim desertified land and start growing crops in a way that reduces their dependence on weather and external factors.

People have already started thinking in this direction as shown by the various projects being undertaken in USA, Canada, UK, Netherlands, Sweden, Korea to name a few. There are vertical farms as well as similar technologies being tried and tested around the world. The problem is of scale, none of these are big enough to practically demonstrate the scope of this technology.

In the process conceived above one may produce a kg of bio-mass with the composition shown in Table 20.1. If an individual consumes 100g of produce generated in this VF, it would be able to provide around 100,000 individuals round the year (assuming production of around 3500 tons of edible biomass as in this case). Although this design and all the related estimations have been done for a representative VF in Berlin, it strives to stand as one of the many possible designs. For that matter, the objective function was to calculate the cost of production for an unit biomass with the aim of maximising the biomass diversity of the system. No objective of profit maximisation have been set since factor and product prices are temporal and region specific.

Table 20.1: Composition of produce



CROPS	COMPOSITION (g)
CARROTS	56
RADISH	41
POTATOES	103
TOMATOES	197
PEPPER	113
STRAWBERRY	44
PEAS	14
CABBAGE	72
LETTUCE	284
SPINACH	39
FISH	37
TOTAL	1000

This work started with scepticism that food grown in Vertical Farms might be exorbitantly expensive to ever become a practicable solution. This technology draws heavily from Space Agriculture, and lack of literature on terrestrial applications leave alone cost analysis fuelled this scepticism further. Concept farms abounding the internet hardly seems practicable and well thought out. This work is first of its kind and contributes a new dimension to agricultural economics.

Having done a detailed system and cost analysis, it seems that although the produce of VF is considerably costlier than mainstream food products, the price is not a world apart. With a € 3.17 to € 6.32 price window there is some hope. Streamlining of this technology and further research could scale down the cost. With this, one can conclude that even with conservative assumptions, growing food in Vertical Farms might be a feasible venture.

However, before that, research needs to be done to tackle the multiple short comings of the VF system. As discussed in the previous Part on Market Analysis, integration of VF systems with renewable energy stations would not only help cut down power costs but since such farms are usually located on infertile lands, it helps utilise such tracts for the purpose of food production. In addition to that if environmental and ecological services like grey water purification, carbon sequestration etc. are integrated into VF, given its performance in comparison to traditional agriculture, the technology definitely stands a chance of proliferation.

This work was initiated in order to do a desktop research on the feasibility of closed system food production technology, otherwise developed for space applications. Now we see that it is theoretically possible to do so and that it is economically as well as environmentally viable. If this body of work succeeds in arousing the interest of German industry or research institutions and prompts them to do further research and development, I would consider this effort worthwhile.

Disclaimer

The front page image is a property of the German Aerospace Agency (DLR) and has been included in this work at the explicit instruction of Mr. Daniel Schubert, who is an official of DLR and the tutor of this thesis.

Fig: 3.1.1 The source of the original background image, which has been downloaded from the internet on 16.12.2011, could not be ascertained. A rightful claim will be duly acknowledged.

Fig: 4.0.1 Is a graphic representation of the CES process conducted by DLR, and has been included in this work at the explicit instruction of Mr. Daniel Schubert, who is an official of DLR and the tutor of this thesis.

Bibliography

[1] Aeroponics-International, 2011. High performance aeroponic systems: Water/nutrient solution-recycling.
URL `www.aeroponics.com/aero32.htm` 10.2

[2] Agrihouse, 2011. Eco-friendly biopesticides: Aeroponic products.
URL `http://www.biocontrols.com/secure/shop/listcats.aspx(Figures4.1)` 10.1, 10.3, A.1

[3] ALSTOM, 2010. Smartcontrol sx, hydro controler system. Product Catalogue.
URL `www.power.alstom.com/hydro` 10.3

[4] Architetti, S. B., 2011. Bosco verticale. Organisational Website.
URL `http://www.stefanoboeriarchitetti.net/?p=207` 2.2.1, 2.2.6

[5] Arthur, R., Baidoo, M. F., Antwi, E., 2011. Biogas as a potential renewable energy source: A ghanaian case study. Renewable Energy 36 (5), 1510 1516.
URL `http://www.sciencedirect.com/science/article/pii/S0960148110005148` 13.1

[6] Ball, E., Wang, S. L., Nehring, R., 2010. Agricultural productivity in the united states: Data documentation and methods. Economic Research Service, USDA.
URL `<http://www.ers.usda.gov/Data/AgProductivity/methods.htm>` 1.4

[7] Banse, M., Meijl, H. v., Tabeau, A. A., Woltjer, G., 2008. Impact of eu biofuel policies

on world agricultural and food markets. 107th Seminar, January 30-February 1, 2008, Sevilla, Spain 6476, European Association of Agricultural Economists.
URL `http://EconPapers.repec.org/RePEc:ags:eaa107:6476` 18.3.1

[8] Baxter, M., 1999. Product design : a practical guide to systematic methods of new product development. Stanley Thornes, Cheltenham, Gloucs. 18

[9] Bhatia, A., 2005. Air conditioning psychrometrics. Online.
URL `http://www.cedengineering.com/upload` 11.2.2

[10] Biocontrols, 2012. Product Calatogue.
URL `http://www.biocontrols.com/secure/shop/item.aspx?itemid=17` 15.6

[11] BKI, 2010. Bki baukosten gebäude 2010: Statistische kostenkennwerte teil 1. B, B

[12] Boyd, C., 2011. Indoor farming is a "plant paradise" in the netherlands. Public Radio International: The World Online August 2, Available at: <http://www.theworld.org/2011/08/video–indoor–farming–is–a–plant–paradise–in–the–netherlands/>. 1, 2.2.2

[13] BrightFarms, 2011. Oranisational Website.
URL `http://brightfarms.com/projects/` 2.2.1, 2.2.5

[14] Bugbee, B., Spanarkel, B., Johnson, S., Monje, O., Koerner, G., 1994. Co2 crop growth enhancement and toxicity in wheat and rice. Advances in Space Research 14 (11), 257 – 267.
URL `http://www.sciencedirect.com/science/article/pii/0273117794903069` 7, 7.2a

[15] Caplow, T., Nelkin, J., 2007. Building-integrated greenhouse systems for low energy cooling. In: 2nd PALENC Conference and 28th AIVC Conference on Building Low Energy Cooling and Advanced Ventilation Technologies in the 21st Century. Crete island,

Greece, pp. 172 176.
URL `http://www.inive.org/members_\area/medias/pdf/Inive/PalencAIVC2007/Volume1/PalencAIVC2007035.pdf` 2.2.1

[16] Chagvardieff, P., d'Aletto, T., André, M., 1994. Specific effects of irradiance and co2 concentration doublings on productivity and mineral content in lettuce. Advances in Space Research 14 (11), 269 – 275.
URL `http://www.sciencedirect.com/science/article/pii/0273117794903077` 7, 7.2a

[17] Checco, L., 2005. Branding for success! : a roadmap for raising the visibility & value of your organization. Trafford, Victoria, B.C. 18.1

[18] Cowing, K., 2011. South pole greenhouse: Model for growing freshies on other worlds.
URL `http://onorbit.com/node/3062` 2.2.3

[19] Cranfield, J., Eales, J., Hertel, T. W., Preckel, P., 1998. Changes in the structure of global food demand. GTAP Working Papers 295, Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University.
URL `http://ideas.repec.org/p/gta/workpp/295.html` 18.3.1

[20] CROPGEN, 2007. Renewable energy from crops and agrowastes. Online.
URL `http://www.cropgen.soton.ac.uk/deliverables.htm` 13.1.4

[21] Despommier, D., 2011. The vertical essay. Online.
URL `http://www.verticalfarm.com/more?essay1` 2.2.11, 18.2.1

[22] DIN, 2006. Din 276-1:2006-11,. B, B, B, B

[23] DLR, 2009. Jülich solar tower power plant: research facility officially handed over to the operator. Tech. rep., Deutsches Zentrum für Luft- und Raumfahrt. 18.4.2.1

[24] DLR, 2011. Desertec - solar power from the desert. Online.
URL `http://www.dlr.de/dlr/en/desktopdefault.aspx/tabid-10200/448-read-255` 18.4.2.1

[25] Elhadj, E., 2005. Experiments in achieving water and food self-sufficiency in the Middle East : the consequences of contrasting endowments, ideologies and investment policies in Saudi Arabia and Syria. Dissertation.Com, Boca Raton (Florida. 18.4.1.1, 18.4.1.1

[26] Elhadj, E., June 2008. Saudi arabian agricultural project: From dust to dust. Online. 18.4.1.1, 18.4.1.1, 18.4.1.1

[27] EPA, 2010. U.s. inventory of greenhouse gas emissions and sink (1990-2005), trends in greenhouse gas emissions, table 2-14. 18.1a, 18.1b

[28] EU, 2010. Agriculture and rural development. Online.
URL `http://eur-lex.europa.eu/budget/data/D2010-VOL4/EN/nmc-titleN123A5/index.html` 18.3.2

[29] Ewing, T., 2010. High solids anaerobic digestion for energy and nutrient recovery. Washington Bioenergy Research Symposium. Center for Sustaining Agriculture and Natural Resources Department of Biological Systems Engineering, Washington State University. 13.1.1, 13.1.4, 13.1.4

[30] Fabian, K., Kollenberg, M. E., 2011. Can urban agriculture feed a hungry world? Spiegel Online International July, Available at: <http://www.spiegel.de/international/zeitgeist/0,1518,775754,00.html>. 2.2.2, 18.2.2

[31] FAO, 2003. World Agriculture: towards 2015/2030 an FAO perspective. Earthscan Publication Ltd. 1.2

[32] FAO, 2008. The state of food insecurity in the world 2008. Online.
URL `<http://www.fao.org/news/story/en/item/8836/icode/>` 1

[33] Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., Helkowski, J. H., Holloway, T., Howard, E. A., Kucharik, C. J., Monfreda, C., Patz, J. A., Prentice, I. C., Ramankutty, N., Snyder, P. K., 2005. Global consequences of land use. Science 309 (5734), 570–574.
URL `http://www.sciencemag.org/content/309/5734/570.abstract` 1.2

[34] Fujitsu, 2012. Wall mounted systems. Product Manual.
URL `http://www.fujitsugeneral.com/wallmountedRLS2_specs.htm` 11.2.4

[35] GothamGreens, 2011. Oranisational Website.
URL `http://gothamgreens.com/our-philosophy/` 2.2.1

[36] Green, R. E., Cornell, S. J., Scharlemann, J. P. W., Balmford, A., 2005. Farming and the fate of wild nature. Science 307 (5709), 550–555.
URL `http://www.sciencemag.org/content/307/5709/550.abstract` 1.1, 18.4.3.1

[37] Gustavsson, J., Cederberg, C., Sonesson, U., 2011. Global food lossesand food waste. In: Save Food Congress, Düsseldorf. 20.2

[38] Halvorson, Partners, 2011. Fundamentals of tall buildings.
URL `http://www.halvorsonandpartners.com/explore/53` 6.2

[39] Huang, J., Rozelle, S., Rosegrant, M., 1999. China's food economy to the twenty first century: Supply, demand, and trade. Economic Development and Cultural Change 47 (4), pp. 737–766.
URL `http://www.jstor.org/stable/10.1086/452430` 1.1

[40] Hubbert, M. K., February 1949. Energy from fossil fuels. Science 109, 103–109. 18.4.1.1

[41] Jorgenson, D. W., Gollop, F. M., 1992. Productivity growth in u.s. agriculture: A postwar perspective. American Journal of Agricultural Economics 74 (3), pp. 745–750.
URL `http://www.jstor.org/stable/1242588` 1.4

[42] Kaufman, P. R., MacDonald, J. M., Lutz, S. M., Smallwood, D. M., 1997. Do the poor pay more for food? item selection and price differences affect low-income household food costs. Economic Report 759, Food and Rural Economics Division, Economic Research Service, U.S. Department of Agriculture.
URL `<http://www.ers.usda.gov/publications/aer759/AER759.PDF>` 1.1

[43] Kendrick, R., 2003. Irrigation fields in quatar. National Geographic Pic of the Day.
URL `http://ngphotooftheday.blogspot.de/2008_11_04_archive.html` 18.4.3

[44] Langhans, R., Tibbitts, T. (Eds.), 1997. Plant Growth Chamber Handbook. North Central Regional Research Publication No. 340, Iowa Agriculture and Home Economics Experiment Station Special Report No. 99. 7, 7.2a

[45] Levenston, M., 2011. Online.
URL `http://www.cityfarmer.info/2011/07/23/` 2.2.2, 2.2.7

[46] Mata-Alvarez, J., S., M., P., L., 2000. Anaerobic digestion of organic solid wastes. an overview of research achievements and perspectives. Bioresource Technology 74 (1), 3–16.
URL `http://www.ingentaconnect.com/content/els/09608524/2000/00000074/00000001/art00023` 13.1.1, 13.1.1

[47] Mitchell, C., 1994. Bioregenerative life-support systems. The American Journal of Clinical Nutrition 60 (5), 820S–824S.
URL `http://www.ajcn.org/content/60/5/820S.abstract` 2.2

[48] NASA, 2002. Baseline values and assumptions document. Tech. rep., National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, Texas. 11.1

[49] NASA, 2004. Advanced life support baseline values and assumptions document. Tech.

Rep. NASA/CR-2004-208941, National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, Texas. 7, 7.1, 7.2, 7.2, 7.3, 9.2

[50] NASA, 2006. Spinoff 2006. Tech. rep., Publication and graphics department NASA Center of AeroSpace Information CASI. 10.1, 10.3, **??**

[51] NewYork-Sunworks, 2012. Organisational Website.
URL `http://nysunworks.org/thesciencebarge/` 2.2.1, 2.2.2

[52] Nicotra-Gebhardt, May 2011. Double inlet centrifugal fans with airfoil blades. Product Catalogue.
URL `http://www.nicotra-gebhardt.com/upload/download-center/catalogue/` 11.2.4

[53] Norland, J., 2006. How high will seer go? Air conditioning/Heating/Refrigeration.
URL `http://www.achrnews.com/articles/how-high-will-seer-go` 11.2.4

[54] Ogawa, A., 2009. Psychrometric chart for sea-level pressure using si units.
URL `http://en.wikipedia.org/wiki/File:PsychrometricChart.SeaLevel.SI.svg` 11.2.1

[55] Omega-Garden, 2012. Organisational Website.
URL `http://www.omegagarden.com/` 2.2.1, 2.2.4

[56] Parawira, W., Read, J., Mattiasson, B., Björnsson, L., 2008. Energy production from agricultural residues: High methane yields in pilot-scale two-stage anaerobic digestion. Biomass and Bioenergy 32 (1), 44 – 50.
URL `http://www.sciencedirect.com/science/article/pii/S0961953407000918` 13.1.1

[57] Piesse, J., Thirtle, C., 2009. Three bubbles and a panic: An explanatory review of recent food commodity price events. Food Policy 34 (2), 119 – 129.
URL `http://www.sciencedirect.com/science/article/pii/S0306919209000116` 1

[58] Plantagon, 2011. Industrial vertical agriculture. Organisational Website.
URL `http://www.symbiocity.org/en/offers/Agriculture/` 2.2.2, 2.2.10, 2.2.2, 19.2

[59] PlantLab, 2012. Organisational Website.
URL `http://www.plantlab.nl/4.0/` 2.2.2, 2.2.8

[60] Rimmer, M. T., Powell, A. A., Oct. 1992. Demand patterns across the development spectrum: Estimates for the aidads system. Centre of Policy Studies/IMPACT Centre Working Papers op-75, Monash University, Centre of Policy Studies/IMPACT Centre.
URL `http://ideas.repec.org/p/cop/wpaper/op-75.html` 18.3.1

[61] SAMA, 2001. Thirty-seventh annual report. Tech. rep., Saudi Arabian Monetary Agency. 18.4.1.1, 18.4.1.1

[62] SAMA, November 2007. Forty third annual report. Tech. rep., Saudi Arabian Monetary Agency.
URL `<http://sama.gov.sa/sites/SAMAEN/ReportsStatistics/ReportsStatisticsLib/>` 18.4.1.1

[63] Savé, R., de Herralde, F., Codina, C., Sánchez, X., Biel, C., 2007. Effects of atmospheric carbon dioxide fertilization on biomass and secondary metabolites of some plant species with pharmacological interest under greenhouse conditions. Afinidad 64 (528), 273 241. 7, 7.2a

[64] Schlacht, I. L., M., M., Rötting, M., Micheletti Cremasco, M., Ono, A., 2009. Space station visual design for the astronauts reliability. In: 60th International Astronautical Congress (IAC), IAC-09.B3.2.9. Daejeon, Republic of Korea. 2.2.2

[65] Schlacht, I. L., Masali, M., Rötting, M., 2008. Visual stimuli for the outer space habitability. In: 59th International Astronautical Congress (IAC), IAC-08.E5.I.1. Glasgow, Scotland. 2.2.2

[66] Simmons, J., October 2009. Technology's role in the 21st century: Food economics and consumer choice why agriculture needs technology to help meet a growing demand for safe, nutritious and affordable food. In: Proceedings of the Cornell Nutrition Conference For Feed Manufacturers. Department of Animal Science of the New York State College of Agriculture and Life Sciences (A Statutory College of the State University of New York), Cornell University, Ithaca, NY 14853. 1, 1.2

[67] Smith, L. C., Haddad, L., 2000. Explaining child malnutrition in developing countries. Tech. Rep. 111, International Food Policy Research Institute, International Food Policy Research Institute, Washington, D.C. 1

[68] Solarpaces, 2006. Solar power and chemical energy systems. Online.
URL `http://www.solarpaces.org/Tasks/Task1/ps10.htm` 18.4.2.1, 18.4.5

[69] Stahl, M., 1997. Strategic management : total quality and global competition. Blackwell, Cambridge, MA. 18.1

[70] Steinfeld, H., Gerber, P., Wassenar, T., Castel, V., Rosales, M., de Haan, C., 2006. Livestock's long shadow environmental issues and options. Food and Agricultural Organisation of the United Nations, Rome. 1.1

[71] ThanetEarth, 2011. Organisational Website.
URL `http://www.thanetearth.com/` 2.2.1, 2.2.1

[72] Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., Polasky, S., Aug. 2002. Agricultural sustainability and intensive production practices. Nature 418 (6898), 671–677.
URL `http://dx.doi.org/10.1038/nature01014` 1.1, 18.4.3.1

[73] Trostle, R., November 2008. Fluctuating food commodity prices: A complex issue with no easy answers. United States Department of Agriculture Economic Research Service.
URL `<http://www.ers.usda.gov/AmberWaves/November08/Features/FoodPrices.htm>` 1

[74] UN, 2003. Accessibility for the disabled - a design manual for a barrier free environment.
URL `http://www.un.org/esa/socdev/enable/designm/AD2-04.htm` 6.2

[75] UN, 2011. World urbanization prospects the 2011 revision.
URL `http://esa.un.org/unpd/wup/pdf/WUP2011_Highlights.pdf` ??, ??, ??

[76] UNFPA, 2011.
URL `http://foweb.unfpa.org/SWP2011/reports/EN-SWOP2011-FINAL.pdf` ??

[77] UNH, 2012. Chlorophyll a, b, and carotenoid absorbance spectra.
URL `http://www.cfb.unh.edu/phycokey/Choices/Chlorophyceae/Chl_a_b_carotenoids_absorption-spectrum.jpg` 9.2.2

[78] UNPD (Ed.), January 2008. AN OVERVIEW OF URBANIZATION, INTERNAL MIGRATION, POPULATION DISTRIBUTION AND DEVELOPMENT IN THE WORLD. No. UN/POP/EGM-URB/2008/01. United Nations Population Division, Population Division, Department of Economic and Social Affairs, United Nations Secretariat.
URL `http://www.un.org/esa/population/meetings/$EGM_PopDist$/$P01_UNPopDiv$.pdf` 1.3

[79] USDA, 1994. The population density map identifies global human population density classes for 1994. NRCS Website.
URL `http://soils.usda.gov/use/worldsoils/mapindex/popden.html` 1.2.1

[80] USDA, 1998. The desertification vulnerability map is based on a reclassification of the global soil climate map and global soil map. NRCS Website.
URL `http://soils.usda.gov/use/worldsoils/mapindex/desert.html` 1.2.2

[81] USDA, 2011. Farm income and costs: Farms receiving government payments. ERS Website.

URL `http://www.ers.usda.gov/briefing/farmincome/govtpaybyfarmtype.htm` 18.3.2

[82] USEIA, September 2011. Electric power monthly september 2011. Tech. rep., U.S. Energy Information Administration, Office of Electricity, Renewables & Uranium Statistics U.S. Department of Energy, Washington, DC 20585.
URL `http://www.eia.gov/electricity/monthly/index.cfm` 18.2.2

[83] VertiCrop, 2011. Oranisational Website.
URL `http://www.verticrop.com/about.html` 2.2.2, 2.2.9

[84] WDI, 2011. World development indicators. Online.
URL `<http://www.google.com/publicdata/directory?hl=enI&dl=en>` 18.4.1.1

[85] Wheeler, R. M.; Mackowiak, C. L. S. J. C. K. W. M., 2011. Growth of soybean and potato at high co2 partial pressures. Advanced Space Research 14 (11), 251–255. 7, 7.2a

[86] Wheeler, T., Ellis, R., Hadley, P., Morison, J., 1995. Effects of co2, temperature and their interaction on the growth, development and yield of cauliflower (brassica oleracea l. botrytis). Scientia Horticulturae 60 (3, 4), 181–197.
URL `http://www.sciencedirect.com/science/article/pii/030442389400725U` 7, 7.2a

[87] Whyte, R., Pery, G., 2001. A rough guide to anaerobic digestion costs and msw diversion. Biocycle.
URL `http://infohouse.p2ric.org/ref/44/43217.pdf` 13.1.1

[88] Wikipedia, 2012. Psychrometrics.
URL `http://en.wikipedia.org/wiki/Psychrometrics` 11.2.2

[89] Wikipedia, 2012. Seasonal energy efficiency ratio.
URL `http://en.wikipedia.org/wiki/Energy_efficiency_ratio` 11.2.4

Appendix A

Fluid delivery system

Table A.1: A list of equipments available in the market

Components required for the aeroponic system

Smartcontroler [2]:
- Price: unknown
- Description: The integrated control system for hydropower plants is organised around high-performance automation cells that carry out all the controlling, regulating and operating functions. In principle, one automation cell controls one hydro turbine/generator unit.

Accumulator tank:
- Price: $279.99
- Description: High pressure nutrient solution accumulator stores solution at 100 psi. Connect unit to our high pressure pump and hydro-control units. Pre-charged to reduce pump cut-in and cut-out cycles.
- Port size: 3/4" stainless steel male pipe thread.
- Solution storage capacity: 2.5 gallons (10 litres).

Digital timer:
- Price: $499.95
- Description: Solid State Repeating Timer for Aeroponic Seed Germination, Cutting Propagation and Continuous growth. Designed to control short burst spray 3 second or 6 second durations and extended spray interval operation - repeatable non-stop operation 24hrs/7days.
- Includes: 24VAC transformer (1A). Features auto-reset upon power interruption, LED indicator status lights and 24V (1A) output connector cable (with wire nuts).
- Size: 2.5 inch x 5 inch x 3 inch (6.4 cm x 12.8 cm x 7.2 cm)

Irrigation components

Pump high-pressure delivery:
- Price: $299.99
- Description: This high pressure diaphragm pump delivers for water and nutrient solutions at 100 psi at full efficiency which used with an accumulator tank and solenoid. Sealed diaphragm construction includes polypropylene housing includes check values and automatic pressure sensor (auto on/off).

Spray jet:
- Price: $9.99
- Description: Right angle spray jet with 0.025" orifice with 1/4 in barb.
- Package size: 1 ea.

Pipes:
- Price: $5.99
- Description: Corrosive resistant tubing. Black vinyl tubing for algae free nutrient solution delivery. Use with black nylon bard adapter for low pressure applications.
- Package size: 10 ft (3m)
- Size: 1/4" ID (3/8" OD) x 10'

Connectors:
- Price: $4.99
- Description: Adapter ELBO 1/4" Female x 1/4" Female
- Black Package Size: 2 ea.

BEYOND^{TM}:

- Price: $49.99
- Description: is derived from natural aquatic materials. Proven aboard NASA's space shuttle and organic growers worldwide. This product is a certified natural plant amendment - not a pesticide.
- Contents: Water... 98.67% Nitrogen (N)... 0.28%/Calcium (Ca)... 0.05%/Total..... 100.00%
- Size: 16 fl . oz. (474 ml) bottle
- Application rate:

- Apply hand or spray: Mix 30 ml into one gallon. Apply often. ~16gallons
- Add to aeroponic or hydroponic reservoir: Mix 5 ml into 10 gal water. ~160gallons

Source: [50]

Appendix B

Building cost[1]

This chapter is an explanation of the use of parametric cost estimation for determining the cost of the building (also refer to B). The cost estimate of building construction or renovation is based on the cost of building construction data base of Baukosteninformationszentrum (BKI). Using this building cost data base, it is possible to estimate the cost of high-rise construction in the early planning phases through a parametric cost estimate. The BKI was founded in 1996 by the chambers of architects of all states with the aim of providing current construction cost data and to develop targeted methods for the determination of construction costs. To this end, the BKI tables come with cost parameters "Kostenkennwerten (KKW)" and planning parameters "Planungskennwerten (PKW)" for the first and second level according to DIN 276 for 74 types of buildings.

The required data is derived from actual construction costs or cost estimation of architectural firms through statistical averaging. In this context, cost variables describe the relationship between the costs of certain categories according to DIN 276-1:2008-12. This is with respect to specific reference units such as gross floor area, excavation or content area of the building site in accordance with DIN 277-3:2005-04 [11]. The design parameters describe the mutual relationships of certain areas and volumes. They are used in the form of percentages or

---

[1] This chapter is based on the document provided by Mr. Conrad Zeidler entitled "Nutzung der Parametrischen Kostenschätzung zur Ermittlung der Gebäudekosten (Anwendungsbeispiel)", which is an annexed chapter in his unpublished Master Thesis.

factors. The DIN standard DIN 276 regulates the planning of the construction costs. It applies in particular for the identification and classification of costs and is applied to the cost of new construction, renovation and modernization of buildings and associated project-related costs. The first level of the cost breakdown, structure the total cost of building for the following seven groups [22]:

- 100: Land
- 200: Preparing and excavation
- 300: Building - Building construction
- 400: Building - Equipment
- 500 External installations
- 600 Internal facilities and art
- 700 Miscellaneous building costs

This approach is used for a rough estimation of costs. In order to determine the exact costs, costs should be broken down into the second level. The following examples show the second level of cost group 300 [22]:

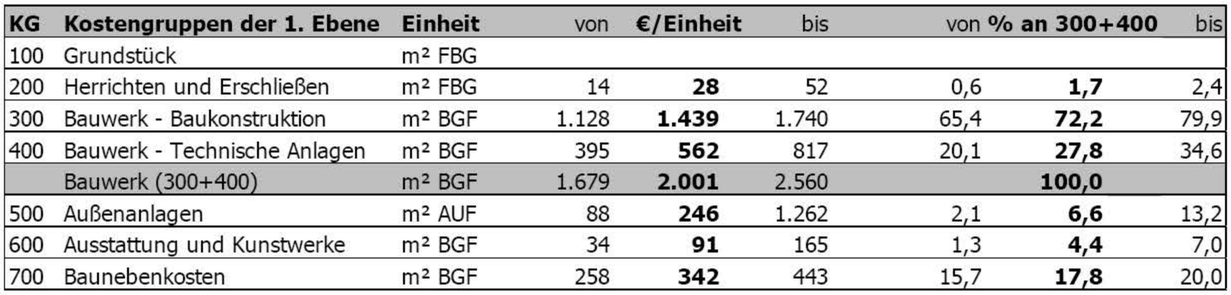
- 310: Pit
- 320: Foundation
- 330: External walls
- 340: Internal walls
- 350: Blankets
- 360: Roofs
- 370: Built-constructional
- 390: Other measures for building structures

For more accurate cost calculations the cost can be further broken down to a third level [22]. The building cost data base will be expanded each year with several new projects. The old cost data is standardized during this process up to the 1st Quarter of the current year. In this case, the building cost data base was used with the publication date of 2010 [11]. The cost of simulation models which were used in this work, the cost of building modifications and new construction are based also on the cost parameters and design characteristics of the construction cost information centre. Based on these data a table in MS Excel was created. This table consists of five main columns and is shown in Table B.1. The lines of the first column range is after the seven cost categories of the first level broken down by DIN 276-1:2006-11. The costs of groups 300 and 400 are for more accurate cost calculation and constitute the second level according to DIN 276-1:2006-11 [22]. Additionally, behind the various cost categories, the information regarding areas/values and units are indicated, by means of which the cost of the building can be estimated. In section 2 of Table B.1 one can find, the values for the area of the building site (FBG), the gross floor area (BGF) and the outdoor unit size (AUG) in this catalogue marked in yellow cells . From the BGF one may calculate the cost categories 310-360 by multiplying the average design parameters in the red shaded cells for the reference surfaces and volumes. The design parameters can be taken from the tables of the BKI data collection for each type of building (see Figure 85 in Appendix B). All the remaining 300, 400, 600 and 700 cost groups use the BGF as a reference for the calculation of costs and have to be just as little as the equivalent of the FBG and the AUG, which also represent the correct reference areas for cost determination. In the last column of this range it is possible that the cost estimates calculated by the model modifies the reference areas/volumes of up to 360- 310th cost group in green shaded cells. These variables are then used in the following range of columns for further calculations.

Table B.1: Simulation model building costs (1: Cost groups, 2 levels with planning parameters; 3: Cost sensitivity, 4 comments, 5: Cost) In the third column area (point 3 in Table B.1) included in the red shaded cells are the minimum, average and maximum values of the cost characteristics of the individual cost groups from the BKI tables (see Table B.4). These serve as a guideline for selection by the user of the model in the green shaded cells selected for entering KKWs. In the last row (point 5 in Table B.1), area are calculated from the selected cost parameters multiplied by the selected reference areas/volumes, the cost of each cost in

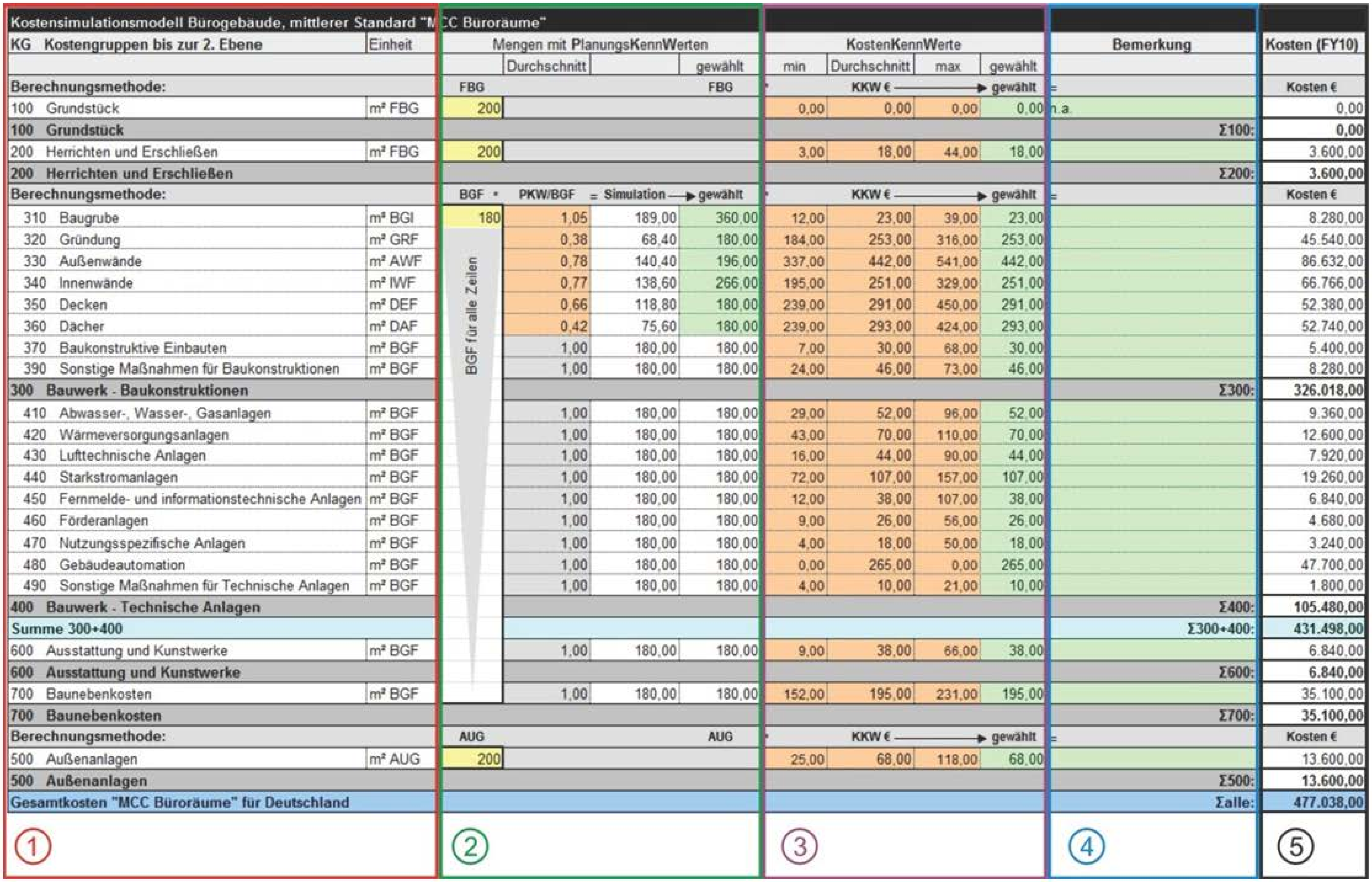
Euro. In addition to the seven cost categories are in the lines of this model, cost data on individual calculation methods for the calculation of the cost of the FBG, the BGF and the AUG. The whole model includes a line in which the total cost is calculated as the sum of the costs of the various cost categories. In the event that the buildings are to be estimated from several floors or in different areas such as laboratory and office areas, the cost of each floor and each area is simulated by different model estimates. The outer shell of this building was also estimated separately and summed with the cost of the other estimates of the total cost of the building. In these cases, it is true that not all costs are accounted for in the estimate of the interior of the building, as has been considered as the cost of group 330 (outer walls) even in the estimation of the outer shell. Which modifications to the described general cost model have been carried out, is evident in the corresponding individual estimates. Additionally, in some models factors for particularly high warehouses or additionally enhanced protection walls in each row are inserted to take into account such structural features.

Table B.2: Cost parameters of Level- 1



KG	**Kostengruppen der 1. Ebene**	**Einheit**	von	**€/Einheit**	bis	von	**% an 300+400**	bis
100	Grundstück	m² FBG						
200	Herrichten und Erschließen	m² FBG	14	**28**	52	0,6	**1,7**	2,4
300	Bauwerk - Baukonstruktion	m² BGF	1.128	**1.439**	1.740	65,4	**72,2**	79,9
400	Bauwerk - Technische Anlagen	m² BGF	395	**562**	817	20,1	**27,8**	34,6
	Bauwerk (300+400)	m² BGF	1.679	**2.001**	2.560		**100,0**	
500	Außenanlagen	m² AUF	88	**246**	1.262	2,1	**6,6**	13,2
600	Ausstattung und Kunstwerke	m² BGF	34	**91**	165	1,3	**4,4**	7,0
700	Baunebenkosten	m² BGF	258	**342**	443	15,7	**17,8**	20,0

Table B.1: Cost Simulation



Kostensimulationsmodell Bürogebäude, mittlerer Standard "MCC Büroräume"												
KG	Kostengruppen bis zur 2. Ebene	Einheit	Mengen mit PlanungsKennWerten				KostenKennWerte				Bemerkung	Kosten (FY10)
				Durchschnitt		gewählt	min	Durchschnitt	max	gewählt		
Berechnungsmethode:			**FBG**			**FBG**	*	**KKW €**	→	**gewählt**	=	**Kosten €**
100	Grundstück	m² FBG	200				0,00	0,00	0,00	0,00	n.a.	0,00
100	**Grundstück**										**Σ100:**	**0,00**
200	Herrichten und Erschließen	m² FBG	200				3,00	18,00	44,00	18,00		3.600,00
200	**Herrichten und Erschließen**										**Σ200:**	**3.600,00**
Berechnungsmethode:			**BGF ***	**PKW/BGF**	**= Simulation**	→ **gewählt**	*	**KKW €**	→	**gewählt**	=	**Kosten €**
310	Baugrube	m² BGI	180	1,05	189,00	360,00	12,00	23,00	39,00	23,00		8.280,00
320	Gründung	m² GRF	BGF für alle Zeilen	0,38	68,40	180,00	184,00	253,00	316,00	253,00		45.540,00
330	Außenwände	m² AWF		0,78	140,40	196,00	337,00	442,00	541,00	442,00		86.632,00
340	Innenwände	m² IWF		0,77	138,60	266,00	195,00	251,00	329,00	251,00		66.766,00
350	Decken	m² DEF		0,66	118,80	180,00	239,00	291,00	450,00	291,00		52.380,00
360	Dächer	m² DAF		0,42	75,60	180,00	239,00	293,00	424,00	293,00		52.740,00
370	Baukonstruktive Einbauten	m² BGF		1,00	180,00	180,00	7,00	30,00	68,00	30,00		5.400,00
390	Sonstige Maßnahmen für Baukonstruktionen	m² BGF		1,00	180,00	180,00	24,00	46,00	73,00	46,00		8.280,00
300	**Bauwerk - Baukonstruktionen**										**Σ300:**	**326.018,00**
410	Abwasser-, Wasser-, Gasanlagen	m² BGF		1,00	180,00	180,00	29,00	52,00	96,00	52,00		9.360,00
420	Wärmeversorgungsanlagen	m² BGF		1,00	180,00	180,00	43,00	70,00	110,00	70,00		12.600,00
430	Lufttechnische Anlagen	m² BGF		1,00	180,00	180,00	16,00	44,00	90,00	44,00		7.920,00
440	Starkstromanlagen	m² BGF		1,00	180,00	180,00	72,00	107,00	157,00	107,00		19.260,00
450	Fernmelde- und informationstechnische Anlagen	m² BGF		1,00	180,00	180,00	12,00	38,00	107,00	38,00		6.840,00
460	Förderanlagen	m² BGF		1,00	180,00	180,00	9,00	26,00	56,00	26,00		4.680,00
470	Nutzungsspezifische Anlagen	m² BGF		1,00	180,00	180,00	4,00	18,00	50,00	18,00		3.240,00
480	Gebäudeautomation	m² BGF		1,00	180,00	180,00	0,00	265,00	0,00	265,00		47.700,00
490	Sonstige Maßnahmen für Technische Anlagen	m² BGF		1,00	180,00	180,00	4,00	10,00	21,00	10,00		1.800,00
400	**Bauwerk - Technische Anlagen**										**Σ400:**	**105.480,00**
Summe 300+400											Σ300+400:	**431.498,00**
600	Ausstattung und Kunstwerke	m² BGF		1,00	180,00	180,00	9,00	38,00	66,00	38,00		6.840,00
600	**Ausstattung und Kunstwerke**										**Σ600:**	**6.840,00**
700	Baunebenkosten	m² BGF		1,00	180,00	180,00	152,00	195,00	231,00	195,00		35.100,00
700	**Baunebenkosten**										**Σ700:**	**35.100,00**
Berechnungsmethode:			**AUG**			**AUG**	*	**KKW €**	→	**gewählt**	=	**Kosten €**
500	Außenanlagen	m² AUG	200				25,00	68,00	118,00	68,00		13.600,00
500	**Außenanlagen**										**Σ500:**	**13.600,00**
Gesamtkosten "MCC Büroräume" für Deutschland											**Σalle:**	**477.038,00**
①			②				③				④	⑤

Table B.3: Cost parameters Level- 2

KG	**Kostengruppen der 2. Ebene**	**Einheit**	von	**€/Einheit**	bis	von	**% an 300**	bis
310	Baugrube	m³ BGI	14	**31**	65	1,2	**2,5**	4,7
320	Gründung	m² GRF	240	**330**	440	5,2	**7,5**	9,6
330	Außenwände	m² AWF	490	**645**	925	27,9	**32,4**	39,5
340	Innenwände	m² IWF	235	**328**	433	16,2	**19,7**	24,3
350	Decken	m² DEF	273	**363**	430	14,8	**19,1**	23,3
360	Dächer	m² DAF	318	**447**	639	7,8	**11,7**	16,1
370	Baukonstruktive Einbauten	m² BGF	12	**41**	104	0,6	**2,7**	7,1
390	Sonstige Baukosten	m² BGF	38	**66**	142	2,7	**4,7**	7,9
							% an 400	
410	Abwasser, Wasser, Gas	m² BGF	41	**58**	99	6,3	**12,1**	19,1
420	Wärmeversorgungsanlagen	m² BGF	60	**83**	121	10,6	**17,4**	27,9
430	Lufttechnische Anlagen	m² BGF	35	**99**	195	4,5	**16,6**	25,0
440	Starkstromanlagen	m² BGF	119	**164**	265	24,5	**31,5**	45,7
450	Fernmeldeanlagen	m² BGF	22	**56**	115	3,5	**9,9**	16,5
460	Förderanlagen	m² BGF	21	**33**	49	0,6	**3,7**	7,3
470	Nutzungsspezifische Anlagen	m² BGF	8	**33**	79	0,3	**3,6**	11,3
480	Gebäudeautomation	m² BGF	28	**57**	86	0,2	**4,1**	12,0
490	Sonstige Technische Anlagen	m² BGF	2	**20**	73	0,1	**1,1**	13,8

Table B.4: Planning parameters for floors and rooms

KG	**Kostengruppen (2. Ebene)**	**Einheit**	von	**Menge/NF**	bis	von	**Menge/BGF**	bis
310	Baugrube	m³ BGI	1,59	**2,07**	3,00	1,07	**1,36**	1,87
320	Gründung	m² GRF	0,43	**0,50**	0,60	0,29	**0,33**	0,38
330	Außenwände	m² AWF	0,96	**1,14**	1,34	0,65	**0,75**	0,84
340	Innenwände	m² IWF	1,23	**1,33**	1,59	0,81	**0,88**	1,09
350	Decken	m² DEF	1,06	**1,12**	1,29	0,69	**0,74**	0,82
360	Dächer	m² DAF	0,50	**0,60**	0,74	0,32	**0,39**	0,47

Persönliche Erklärung:

Hiermit erkläre ich, dass ich die vorliegende Arbeit selbstständig und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe. Alle Stellen, die wörtlich oder sinngemäß aus veröffentlichten und nicht veröffentlichten Schriften entnommen wurden, sind als solche kenntlich gemacht. Die Arbeit ist in gleicher oder ähnlicher Form oder auszugsweise im Rahmen einer anderen Prüfung noch nicht vorgelegt worden.

Bonn, den 17. Juli 2012

(Chirantan Banerjee)