Feasibility Study: Vertical Farm EDEN

Institute of Space Systems
Dept. of System Analysis Space Segment

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DLR

EDEN

Institute of Space Systems

System Analysis Space Segment

CE-Study: Vertical Farm EDEN

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Acronyms and Abbreviations

:envihab	Environmental Habitation
AD	Anaerobic Digestion
BKI	Baukosteninformationszentrum
CE	Concurrent Engineering
CEA	Controlled Environment Agriculture
CEF	Concurrent Engineering Facility
COP	Coefficient of Performance
CROP	Combined Regenerative Organic-food Production
CS-Eu:CROPIS	Compact Satellite - Euglena: Combined Regenerative Organic-food Production In Space
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DLR-RY	DLR-Institute of Space Systems
EC	Electrical Conductivity
EDEN	Evolution & Design of Environmentally-closed Nutrition-Sources
EER	Energy Efficiency Ratio
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre
FLASH	Facility of Laboratories for Sustainable Habitation
GHM	Greenhouse Module
HI	Harvest Index
HRT	Hydraulic Retention Time
HVAC	Heating, Ventilation and Air-Conditioning
ISRU	In-Situ Resource Utilization
ISS	International Space Station
ISU	International Space University
KKW	Kostenkennwerten
LED	Light Emitting Diode
LSS	Life Support System
NASA	National Aeronautics and Space Administration
NDS	Nutrient Delivery System
OLR	Organic Loading Rate
PKW	Planungskennwerten
PPF	Photosynthetic Photon Flux
RH	Relative Humidity
RY-SR	Department System Analysis Space Segment
RY-ST	Department System Analysis Space Transport
SBIR	Small Business Innovation Research
SEER	Seasonal Energy Efficiency Ratio
TS	Total Solids
VF	Vertical Farm
VS	Volatile Solids

Executive Summary

In this report the technical design and economic analysis of a Vertical Farm (VF), a high-rise building used for the cultivation of food crops, is presented. Vertical Farms are posited as a potential solution regarding the global food demand by allowing increased crop growth per land area. A Vertical Farm offers the possibility of cultivating crops year-round in an optimized, controlled environment, regardless of external conditions. As with many new technologies, it is the technical and economic feasibility which eventually determine whether Vertical Farms will be built. However, until now, no study has been performed to determine the actual production costs and achievable output of a Vertical Farm.

During a Concurrent Engineering (CE) study at the Institute for Space Systems of the German Aerospace Center (DLR), a Vertical Farm was designed and cost analysis was performed to determine the capital and operating costs, associated with the design.

A semi closed-loop Vertical Farm design was created, which can cultivate plants and produce fish. Water is recycled using filtration and recovery systems. The waste resulting from the plant cultivation- and fish farming processes is used for power- & heat generation, fish feed supplement, and to generate new bio fertilizer.

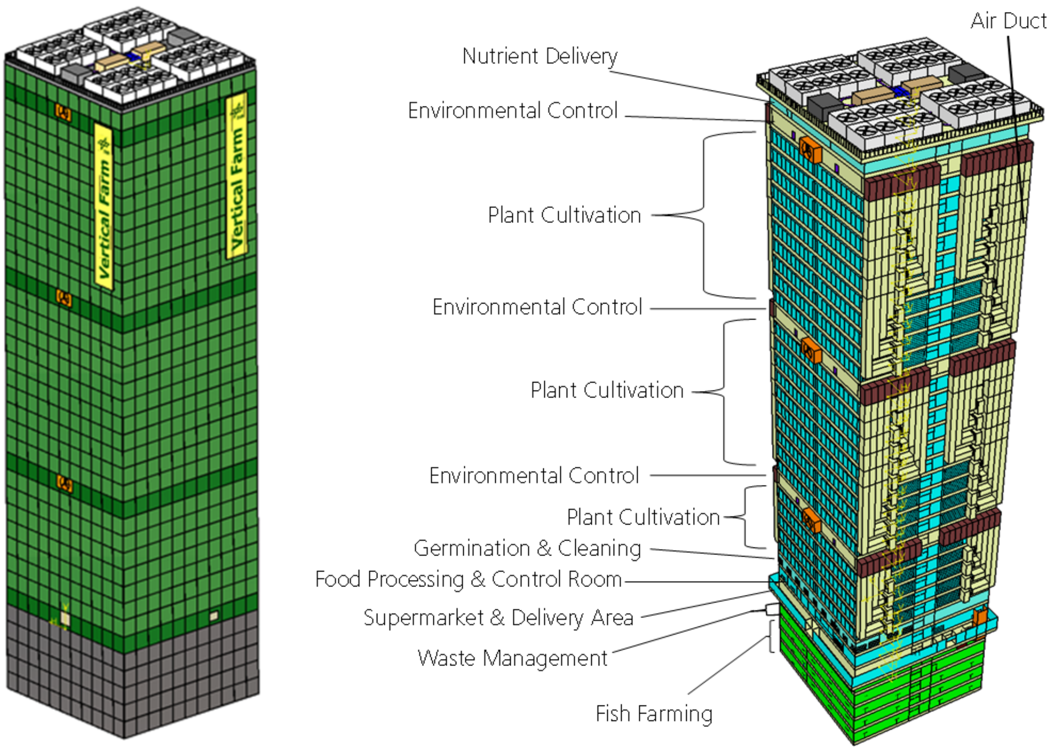


Figure 1: Outer and inner structure of the Vertical Farm

The Vertical Farm design (compare Figure 1) is a building with 37 floors and a total height of 167,5 meters (while 5 floors are beneath ground level). The building has a square footprint and the external dimensions of 44 by 44 meters. The actual available area for the different floor designs is 40 by 40 meters. The remaining area is reserved for structural element and air ducts.

There are 25 Plant Cultivation Floors in the building. These floors are used for the cultivation of ten different crop species. A total edible biomass output of around 13,3 tons/day and about 4.900 tons/year can be achieved with a total grow area of ca. 93.000 m².

Aside from plant cultivation, three Fish Farming Floors are dedicated to the cultivation of Tilapia fish. A total of ca. 2.100 Tilapia fish can be produced per day, which corresponds to roughly 280 kg/day and 100 tons/year of Tilapia filet.

Calculations and best engineering estimates are made for the power demands of the all subsystems of the Vertical Farm. It is found that the peak power consumption is around 21.300 kW and the energy consumption is roughly 405.500 kWh/day.

There is an increase in yield of all crops in the Vertical Farm. To produce an equal amount of crops than produced in a VF (with a footprint of 1.936 m²), an area of 216 ha of traditional agriculture land is needed. This leads to an agricultural land increase factor of 1.115, compared to the footprint of the VF building.

Table 1 summarizes all key features and parameters of the Vertical Farm, elaborated in this study.

Table 1: Summary of the Vertical Farm study results: Baseline Scenario [FY12]

Building Dimension	
Amount of floors	37
Plot area	50 x 50 [m²]
Food print of building	44 x 44 [m²]
Building height	167,5 [m]
Floor-to-floor height	4,5 [m] (5th basement: 5,5 [m])
Excavation	44 x 44 x 23,5 [m³]
Total growth area	92.718 [m²]
Amount of floors	
Germination Floor	1
Plant Cultivation Floor	25
Fish Farming Floor	3
Nutrient Delivery System Floor	1
Environmental Control Floor	3
Food Processing Floor	1
Waste Management Floor	2
Basement (Supermarket Floor)	1
Waste	**Output per year [ton/year]**
Non-edible fish output and fish floor waste	394
Fresh inedible biomass yield with aeroponics	3.420
Food	**Edible Biomass Yield with aeroponics [ton/year]**
Lettuce (4 floors)	1.479
Cabbage (2 floors)	356
Spinach (1 floor)	205
Carrots (2 floors)	281
Radish (1 floor)	215
Tomatoes (3 floors)	978
Peppers (2 floors)	559
Potatoes (5 floors)	494
Peas (4 floors)	69
Strawberry (1 floor)	219
Total Plant Biomass Yield per VF	**4.854**
Tilapia Filet	**102**
Total Food Yield per VF	**4.957**
By-products	**Production per year [m³]**
Methane	717.444
Carbon dioxide	358.722

Resource	Consumption per year
Electricity	148.001.295 [kWh]
Carbon dioxide	463.550 [m^3]
High-protein fish feed	131 [t]
Beyond ™ fertilizer	10.859 [L]
Personnel	60 [people]
Water	8.274.550 [L]
Cost source with 20% margin	**Cost per year [k€]**
Initial Building & Equipment*	14.101
Equipment Maintenance and Replacement**	14.522
Power	28.416
Seeds	55
Nutrients (Beyond ™)	1.066
Fish feed	395
Water	18
Personnel	3.600
Total costs per year with 20% margin	**62.173**
Minimum required average food price	**12,54 €/kg**

* Initial building and equipment costs (of 284669 k€) are amortized over 30 years, with no residual value. An interest rate of 3,0% is assumed.
** Assumed to be 10% of initial equipment costs per year.

1 Introduction

Hundreds of millions of people around the world do not have access to sufficient food. With the global population continuing to increase, the global food output will need to drastically increase to meet demands. At the same time, the amount of land suitable for agriculture is finite, so it is not possibly to meet the growing demand by simply increasing the use of land. Thus, to be able to feed the entire global population, and continue to do so in the future, it will be necessary to drastically increase the food output per land area.

One idea which has been recently discussed in the scientific community is called Vertical Farming (VF), which cultivates food crops on vertically stacked levels in (high-rise) buildings. The Vertical Farm, so it is said, would allow for more food production in a smaller area. Additionally, a Vertical Farm could be situated in any place (e.g. Taiga- or desert regions, cities), which would make it possible to reduce the amount of transportation needed to deliver the crops to the supermarkets.

The technologies required for the Vertical Farm are well-known and already being used in conventional terrestrial greenhouses, as well as in the designs of bioregenerative Life Support Systems for space missions. However, the economic feasibility of the Vertical Farm, which will determine whether this concept will be developed or not, has not yet been adequately assessed.

Through a Concurrent Engineering (CE) process, the DLR Institute for Space Systems (RY) in Bremen, aims to apply its know-how of Controlled Environment Agriculture (CEA) Technologies in space systems to provide valuable spin-off projects on Earth and to provide the first engineering study of a Vertical Farm to assess its economic feasibility.

1.1 Background

DLR (Deutsches Zentrum für Luft- und Raumfahrt) is Germany's national research center for aeronautics and space. DLR's extensive research and development work in the fields of aeronautics, space transportation and energy is integrated into national and international cooperative ventures, placing DLR at the forefront of the German space technology. Appointed as the authoritative entity for the forward planning, coordination and implementation of the German space programme by the federal government, DLR is directly responsible for the international representation of Germany's interests within the global space community.

Figure 2: DLR Institute of Space Systems in Bremen

Approximately 7.000 people work for DLR. The center comprises 32 institutes and facilities at 16 locations situated mainly throughout Germany. These include the headquarters in Cologne, the Space Agency in Bonn as well as sites in Augsburg, Berlin, Braunschweig, Bremen, Goettingen, Hamburg, Jülich, Lampoldshausen, Neustrelitz, Oberpfaffenhofen, Stade, Stuttgart, Trauen and Weilheim. DLR also has offices in Brussels, Paris, Washington and Singapore. In 2007, DLR unveiled its new Institute of Space Systems (RY) in Bremen (see Figure 2). The Institute's aim is to investigate and evaluate complex astronautic systems in the context of space research given consideration of technological, economic as well as socio-political aspects. Furthermore, the dynamic team of employees at the institute develops space missions on national and international levels.

The project leading department „System Analysis Space Segment" (RY-SR) constitutes, together with the department „System Analysis Space Transport" (RY-ST), the division of System Analysis within the Institute of Space Systems (RY). The major task of the department RY-SR is to analyse, develop and evaluate space systems and technologies, on the basis of Systems- and Concurrent Engineering methods.

In 2011, RY-SR launched a research initiative called EDEN - Evolution & Design of Environmentally-closed Nutrition-Sources. The research goal of this programme is to design and evaluate greenhouse concepts for orbital and planetary research stations and habitats. The focal point is set on Controlled Environment Agriculture (CEA) technologies and the transformation and integration of these technologies into space-proven hardware solutions.

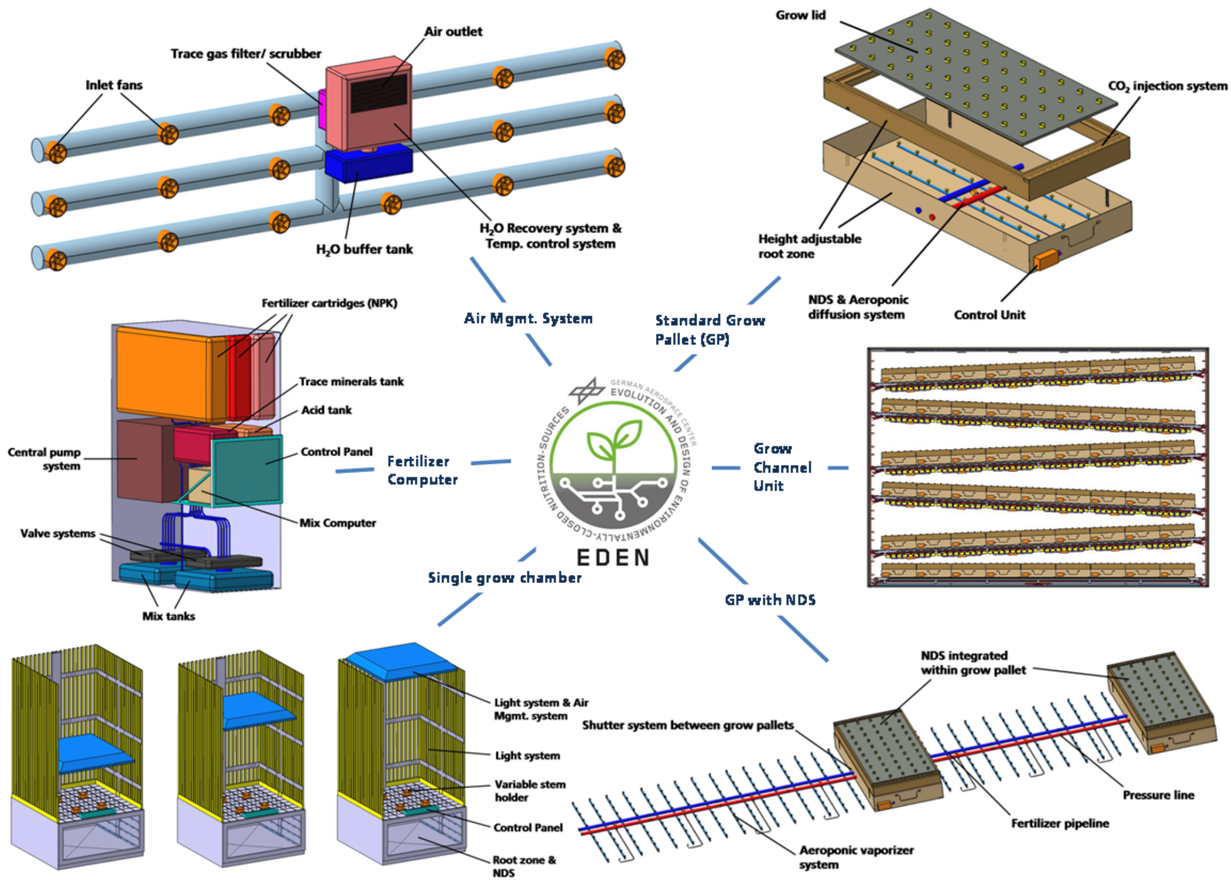
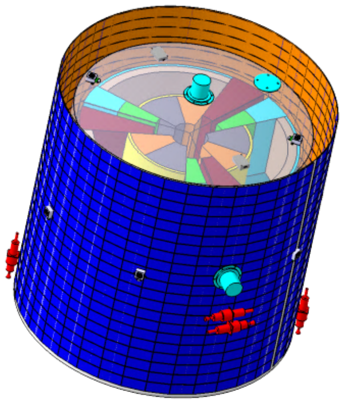
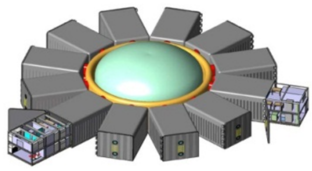
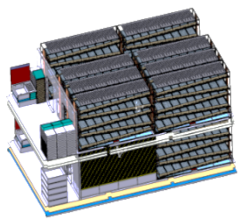


Figure 3: Extract of some systems and subsystems within the DLR EDEN program

Among other research partners, the EDEN initiative has established a network including the DLR Institute of Aerospace Medicine (Cologne) with its future research laboratory *:envihab* (environmental habitation). As a ground-based interdisciplinary and international research facility, *:envihab* will support the utilization of the International Space Station (ISS) and help to progress research beyond the ISS and eventually into human deep space exploration.

Table 2: CE-Studies at the DLR Bremen related to greenhouses, habitation and CEA Technologies

CS-Eu:CROPIS *(December 2011)*	The CE-Study CS-Eu:CROPIS (Compact Satellite - Euglena: Combined Regenerative Organic-food Production In Space) assessed the feasibility of the use of food-production equipment as payload for the DLR's Compact Satellite Mission (Launch date: 2016). The CE-study was performed to design the satellite, which will be mainly built at the DLR Bremen site. Significant aspects to test during this Compact Satellite's mission are the breeding of edible plants in space (seed to seed), respectively the photosynthetic activity under different low gravity conditions (active spin satellite for simulating low gravity 0,1 g, Moon and Mars gravity levels) and the use of Euglena for producing oxygen on demand and to support the degradation of human urine to a nitrate fertilizer solution. Several departments of the DLR and the University of Erlangen (Germany) participated in the CE-Study.	
FLASH *(August –September 2011)*	The CE-Study FLASH (Facility of Laboratories for Sustainable Habitation) focused on the concept development of a closed-loop habitat for technology testing, with different recycling applications and In-Situ Resource Utilization (ISRU) processes. The facility consists of an EVA terrain hall, a control center, a public engagement area and 12 functional modules: air module, animal module, food processing facility, greenhouse, ISRU module, living module, sickbay, waste module, water module and workshop facility. The main study points were the overall configuration, equipment-level subsystem description and the mass flow relationships between the modules. DLR, University of Bremen, University of applied sciences of Dresden, Liquifer Systems Group, Technical University of Berlin and ISU (International Space University) took part in this study.	 *Overall configuration*  *Greenhouse module*
Antarctic GHM *(ASG topic from Dec. 2011-Feb. 2012)*	This study was perfomred by the DLR internal Advanced Study Group (ASG), which is a think tank within the CEF infrastructure. The Antarctic GHM comprised all necessary S/S needed for the cultivation of different crops for a remote research station at the South Pole. With the standard size of a 40' food container this automated greenhouse module can produce fresh food (only on a supplement basis) for a 20-30 person crew. Main goal was to calculate the overall edible biomass output, S/S accommodation and power demand.	 

For these reasons *:envihab* forms a fundamental component of DLR's research into space exploration, but with significant potential benefits for terrestrial applications as well. Here, a close cooperation within the project CROP (Combined Regenerative Organic-food Production) takes place. The goal of this research project is to develop a bio-regenerative Life-Support System (LSS) with main focal point on urine degradation, solid waste recycling and food production. The research network has gathered a solid knowledge base with respect to cutting-edge plant cultivation processes for extra-terrestrial habitats.

Furthermore, in January 2009 the Concurrent Engineering Facility (CEF) was launched into operation in order to perform concept studies and system analyses. The process, the architecture and the initial software (S/W) had been adopted from ESA-CDF. RY-SR develops and utilizes computer-aided methods for evaluating space concepts regarding applicability, acceptance, feasibility and cost. Here, RY-SR is responsible for managing and organizing this systems engineering laboratory. More than 30 studies have been performed in the CEF since 2009.

RY-SR has combined several times its competences in Concurrent and Systems Engineering, in order to deeply investigate in Controlled Environment Agriculture (CEA) technologies, their implementation in extra-terrestrial greenhouses and closed-loop habitation concepts. Feasibility studies in the CEF and the consequent acquisition of experts' know-how in the involved disciplines has opened a significant research direction not only within RY-SR, but also within the Institute of Space Systems and DLR as a whole. Table 2 lists and describes an extract of studies performed in the CEF with respect to Life Support Systems (LSS) and greenhouse modules.

1.2 Concurrent Engineering Approach

To investigate and define the technical concept of a Vertical Farm, a Concurrent Engineering (CE) Study at DLR Bremen has been performed. The CE-study comprised the analysis and the development of all subsystems necessary for a Vertical Farm.

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 left). 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 right).

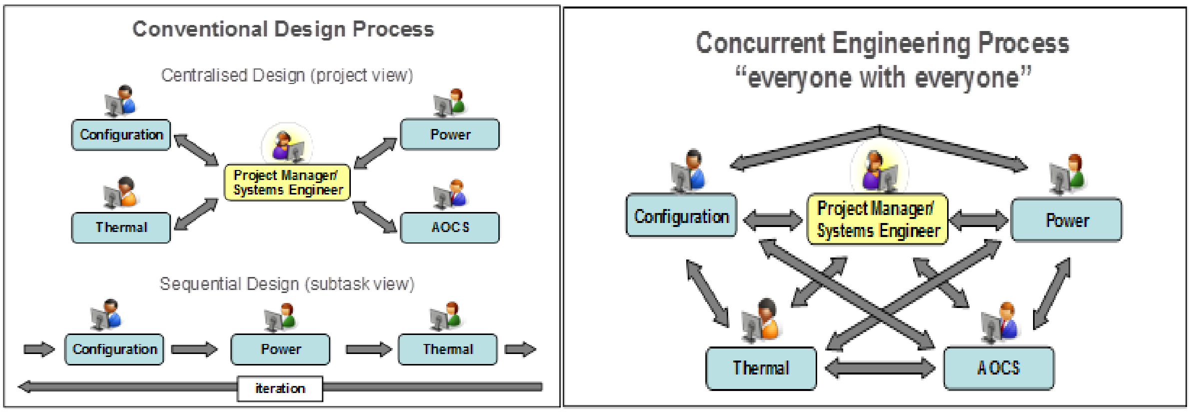


Figure 4: The Concurrent Design approach compared to projections of conventional design process.

The DLR's Concurrent Engineering Facility in Bremen, see Figure 5, is derived from the Concurrent Design Facility at ESA's ESTEC (European Space Research and Technology Centre), which has already been in operation for more than ten years.

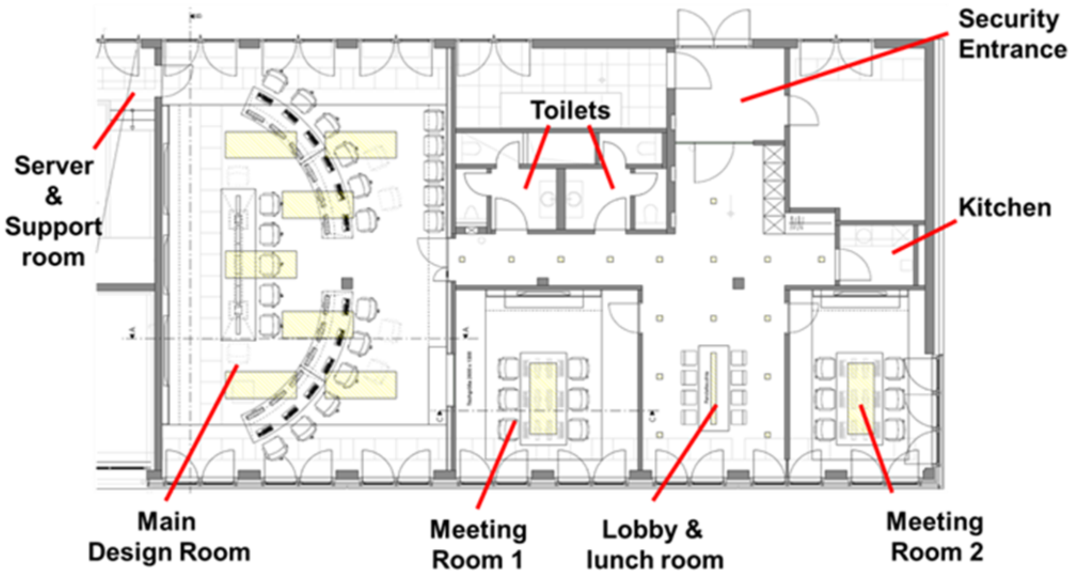
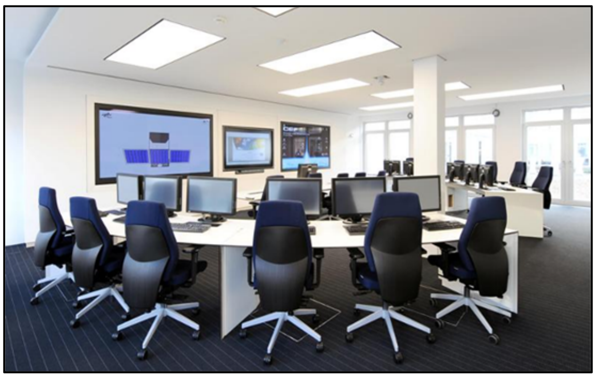


Figure 5: Concurrent Engineering Facility (CEF) at DLR Bremen

Bremen's DLR-CEF has one main working room where the whole design team can assemble and each discipline is supplied with an own working station for calculations and interaction with a special design tool developed by ESTEC. Three screens, one of them interactive, allows display of data in front of the team. Further working positions are provided in the center of the working area and are usually reserved for customers, PIs, guests as well as the team leader and possibly the systems engineer. Two more splinter rooms provide the design team with separated working spaces where sub-groups can meet, discuss and interact in a more concentrated way.



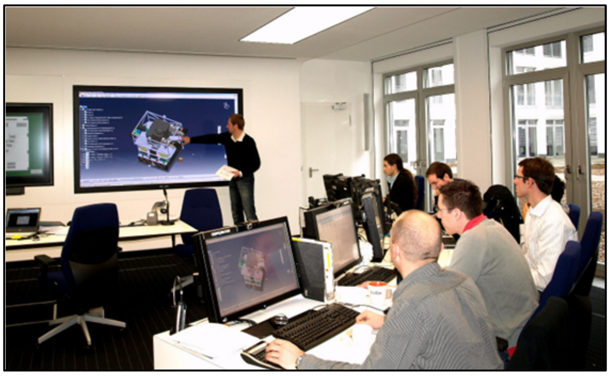


Figure 6: Concurrent Engineering Facility main room (left), working during CE-study phase (right) at DLR Bremen

The major advantages of the CE-process are:

- Very high efficiency regarding cost & results of a design activity (Phase 0, A)
- Assembly of the whole design team in one room facilitates direct communication and short data transfer times
- The team members can easily track the design progress, which also increases the project identification
- Ideas and issues can be discussed in groups, which brings in new viewpoints and possible solutions; avoidance and identification of failures and mistakes

The CE-Process is based on simultaneous design and has four Phases ("IPSP-Approach"), as can be seen in Figure 7:

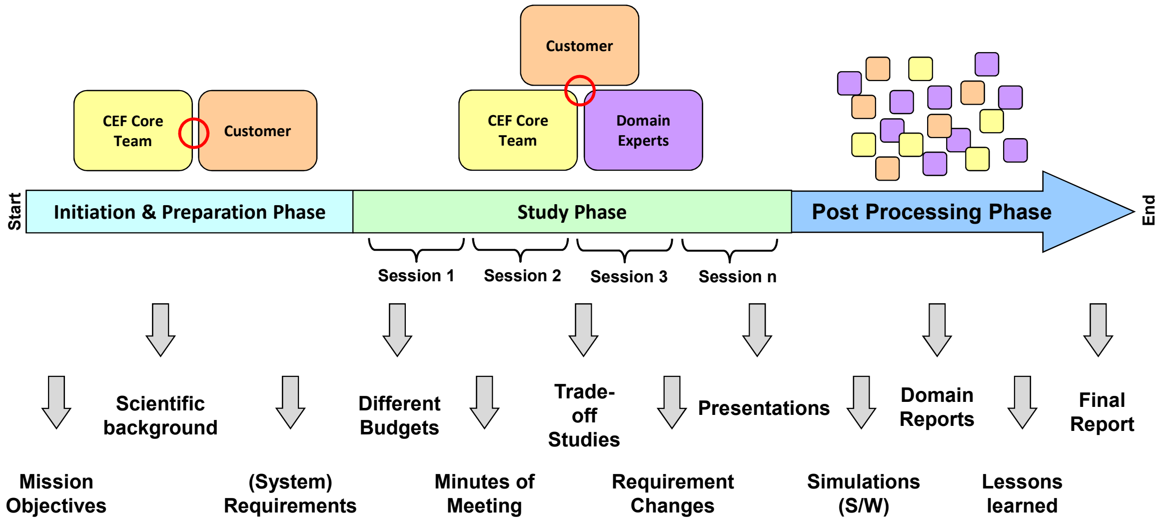


Figure 7: Concurrent Engineering process

1. Initiation Phase (starts weeks/months before using the CE-facility):
   - Customer (internal group, scientists, industry) contacts CE-team
   - CE-team-customer negotiations: expected results definition, needed disciplines

2. Preparation Phase (starts weeks before using CE-facility):
   - Definition of mission objectives (with customer)
   - Definition of mission and system requirements (with customer)
   - Identification and selection of options (max. 3)
   - Initial mission analysis (if applicable, e. g. based on STK)
   - Final definition and invitation of expert ensemble, agenda definition

3. Study Phase:
   - K/O with presentations of study key elements (goals, requirements)
   - Starting with first configuration approach and estimation of budgets (e.g. mass, power, volume, modes) on subsystem level
   - Iterations on subsystem and equipment level in several sessions (2- 4 hours each); trading of several options
   - In between offline work: subsystem design in splinter groups
   - Final Presentation of all disciplines / subsystems

4. Post Processing Phase:
   - Collecting of Results (each S/S provides Input to book captain)
   - Evaluation and documentation of results
   - Transfer open issues to further project work

1.3 Study Objectives and Expert Domains

The main criteria which will determine the feasibility of the Vertical Farm is the minimum cost of the produced food which will allow the Vertical Farm to break-even. Should this value be much higher than the cost of crops produced in fields or conventional greenhouses, then the Vertical Farm is unlikely to succeed.

Thus, the study carried out at DLR Bremen had to determine the potential food output of the Vertical Farm, as well as the start-up and operating costs. To accomplish this, a concept of a Vertical Farm needed to be designed and its performance had to be calculated.

The technologies required for the Vertical Farm are already available. Until now, however, no study has been performed to design a Vertical Farm and determine the costs and earnings associated with it.

The objective of this study, therefore, is to determine the technical and the economic feasibility of a Vertical Farm.

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

Of course there are many design options for a Vertical Farm. For example some designs follow multi-crop strategies and others follow mono-crop strategies. Since the present study shall display only exemplary feasibility study, the design team decided to go with the multi-crop strategy (meaning the building produces a variety of different crops like e.g. tomato, lettuce, strawberries). For more information refer to Chapter 2.2 (global assumptions). Of course the design choices will impact the technical and economic feasibility of a concept. Thus, several scenarios are investigated to determine the effects of a few of the decisions made during the Vertical Farm design. Specifically, the impact of carrying out fish farming, waste management and water recovery in the Vertical Farm are analysed during the alternative scenario analysis (compare chapter 13).

While the Vertical Farm provides potential advantages over traditional agriculture, such as 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.

Since the study's objective is to display an exemplary design of a Vertical Farm, several study domains are introduced in order to account for the different subsystems as well as the challenges that occur with the Vertical Farm design. Figure 8 displays the expert domains. Besides the usual plant cultivation related domains like *Nutrient Delivery*, *Environmental Control, Lighting/Power, Biology & Plant Selection*, *Plant Cultivation* and *Germination Floor* the CEF Team decided to include also other domains necessary for a solid feasibility study. For example the domain *Structure & Configuration* has the task to create the superstructure of the building itself, but also to visualize the floors within the building (mainly done by CATIA drawings).

Furthermore, a domain for fish farming and waste management is created as optional floors within the Vertical Farm. The *Food Processing* and the *Harvest & Cleaning* domains act as interface towards the supermarket in the basement of the building and deal with all work steps from harvesting, cleaning and packaging of the raw crops (and fish) as well as cleaning the used grow pallets (incl. sterilization) and transport them back to the plant floors.

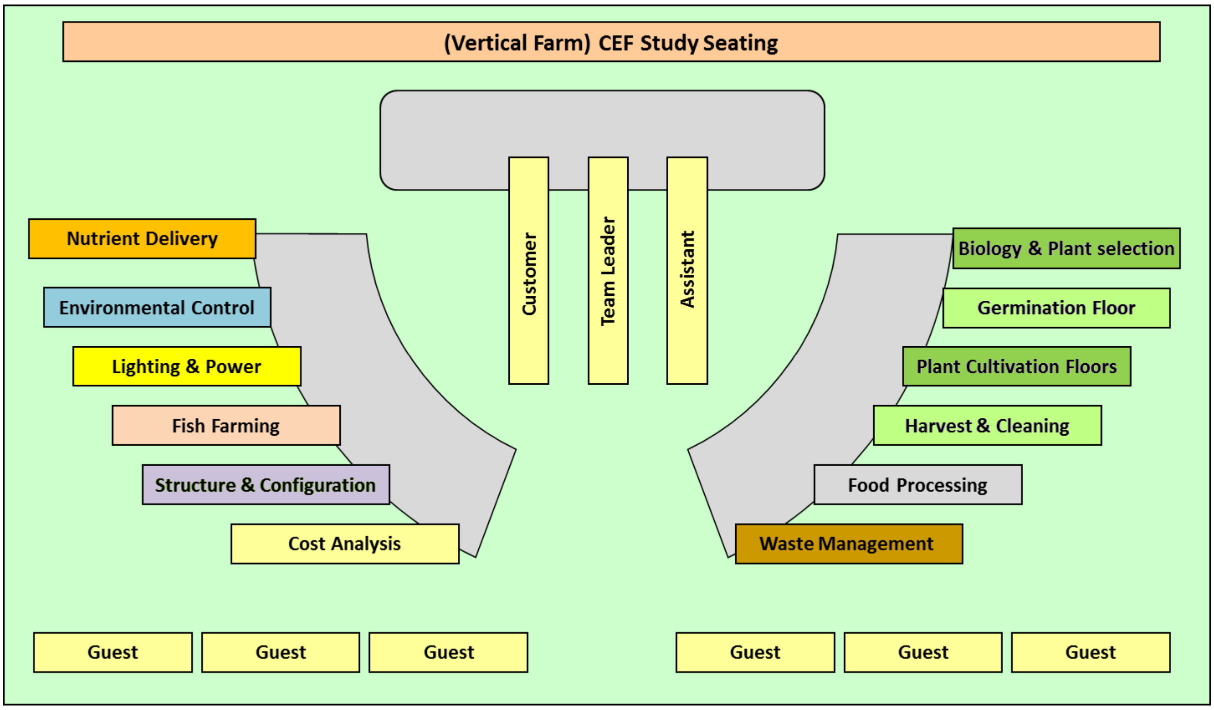


Figure 8: Vertical Farm CE study domains

A cost domain examines all necessary costs (non-recurring & recurring) in order to establish a cost estimate for the overall endeavour. The Team Leader (incl. assistant) is responsible to guide the design team and to moderate the sessions. Main task is to facilitate the information flow between the other domains as well as to create consensus if necessary. The customer role is mainly responsible to decide critical design issues. During the study this role was performed in personal union with the team leader domain.

1.4 Document Information

This report shows the concept design of the Vertical Farm, as well as the performance analysis. The pre-CEF work, including system analysis and initial trade-offs, is detailed in Chapter 2. In the following several chapters the designs of the subsystems of the Vertical Farm are described, starting with the actual building in Chapter 3. Following the discussion of the superstructure, in Chapter 4 the germination system design, as well as the cleaning system for the Vertical Farm is presented. In Chapter 5 the crop selection and the design of the plant cultivation system is covered. Following this, in Chapter 6 the design of the fish farms is shown. In Chapter 7 the details of the nutrient delivery system, which is responsible for the delivery of water and nutrients to the crops, is discussed. Equally important for the cultivation of crops are the lighting system, which is covered in Chapter 8 and the environmental control system, discussed in Chapter 9. In Chapter 10 the food processing subsystem, which provides the crucial step between farm and consumer, is discussed and in Chapter 11 the processing of in-edible by-products of the Vertical Farm in the waste management system is covered. Then, finally, in Chapter 12 an economic analysis of the Vertical Farm design is carried out to determine its potential, while in Chapter 13 three alternative Vertical Farm scenarios are examined to assess the economic impact of design decisions. At the end of the report, the findings of the CEF-study are summarized, conclusions are drawn and a number of issues for future study are discussed.

2 Systems

This chapter shows the system analysis for the Vertical Farm. A functional breakdown is given, as well as subsystem and interface definitions. Furthermore, a discussion is presented on some initial trade-offs which needed to be performed for subsystems before the CE-study could begin.

2.1 System Analysis

The primary function of the Vertical Farm is to produce edible biomass, through crop cultivation and / or animal husbandry.

Based on this requirement for 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, wet air or trace gases.

A (partial) overview of the 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 9.

The functions are color-coded according to the subsystem which will handle that specific task. The domains which have been defined for this CE-study can be seen in Figure 8, along with their positions in the CEF main room. It should be noted that this is only one of various possible system breakdowns which can be established for the Vertical Farm.

While the system breakdown 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.

It is not possible to design each subsystem separately, then put the design together and end up with a fully-functioning, optimized Vertical Farm. During the design process the teams need to work closely together to deal with the interfaces between the 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 system analysis. For the Vertical Farm the interface definitions can be found in the N^2-chart in Figure 10. The N^2-chart is a system engineering tool used to show the interfaces between systems, subsystems or even components [2]. On the diagonal of the N^2-chart the systems of the Vertical Farm are listed. The external environment is also taken into account, to show the resource flows in and out of the building.

Interfaces between the systems are shown in the off-diagonal blocks and flow clockwise. For example, the block directly to the right of the nutrient delivery system block and directly above the environmental control system block indicates that heat flows from the nutrient delivery system to the environmental control system. Another example is the lighting system, which provides light for the plant cultivation system and also the germination and cleaning system.

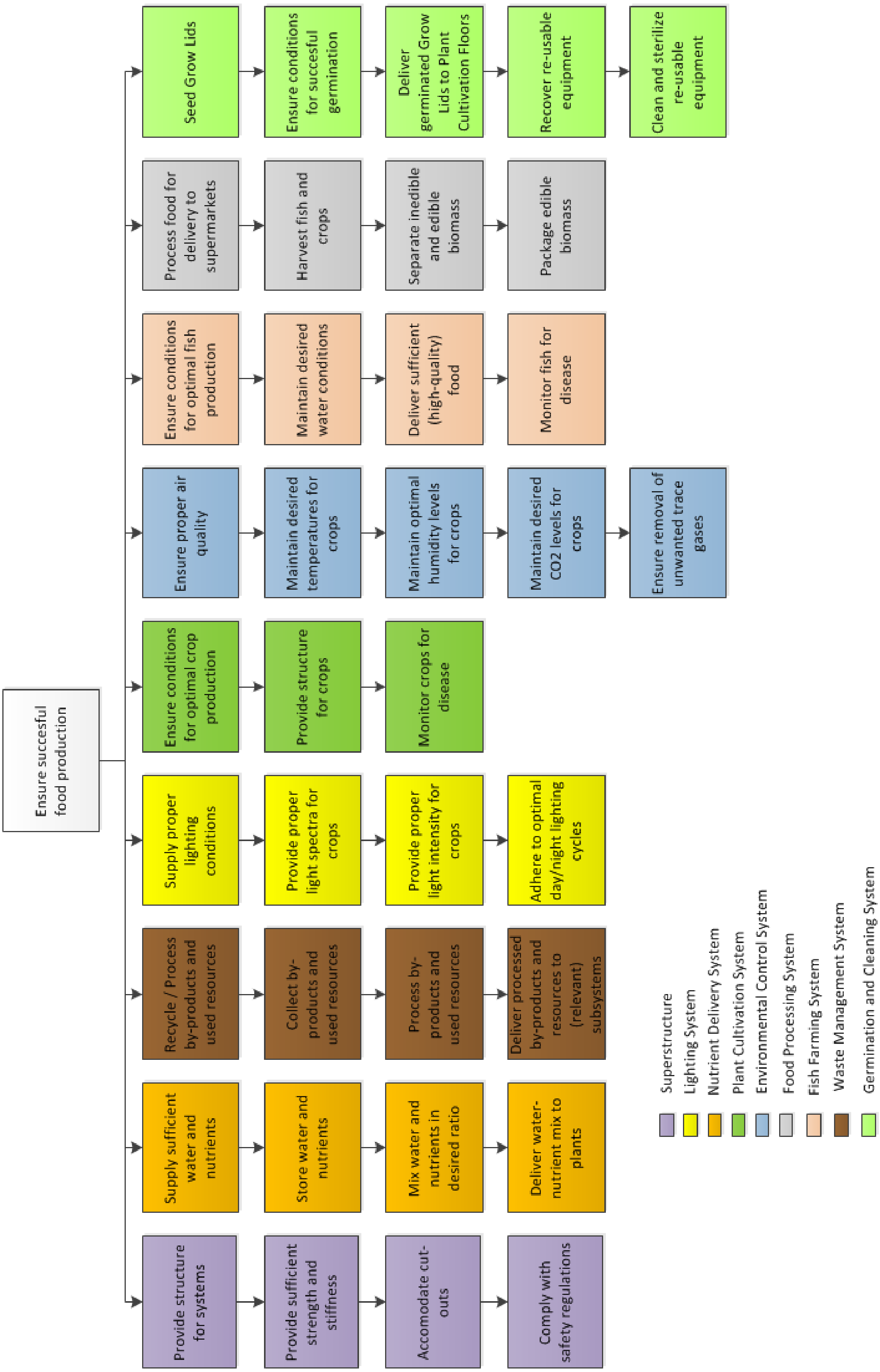


Figure 9: Functional Breakdown for the Vertical Farm

Note that since the interface definitions are dependent on subsystems, it may vary depending on the specific system breakdown which is used. Also note that the lighting system is considered to consist only of the LED panels used for plant germination and cultivation, hence it does not provide lighting for other systems.

Structure	Housing	Housing	Housing	Housing	Housing	Housing	Housing	Housing	
	NDS	heat		Water, nutrients	Water			Water, nutrients	
	water	**ECS**		CO_2, 'dry' air					Trace gases, heat, air
		heat	**LS**	Light				Light	
		Water, heat, trace gases, wet air		**PCS**		Fresh crops	Excess nutrient solution		
	Nitrate-rich (waste) water	heat			**FFS**	Fish	Fish waste, excess food		
		heat			Fish food (inedible biomass)	**FPS**	Inedible fish mass, inedible crop mass	Dirty re-usable equipment	Processed, packaged food
	Water, nutrients, power	CO2, water power, heat	power	power	power	power	**WMS**	Water, nutrients, power	Digestate, left-over waste
		Water, heat, trace gases, wet air		Germinated Grow Lids		Clean, sterile, equipment		**G&CS**	
power	Water, power	Air, CO_2, power	power	power	Power, fish food, water	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
- Germination and Cleaning System
- External

Figure 10: N²-chart interface definitions for the Vertical Farm

2.2 Global Assumptions, Options and Trades

As could be determined from the system breakdown, the Vertical Farm designed during the CE-study will produce edible biomass through a combination of crop cultivation and fish farming. Figure 11 shows the floor distribution of the Vertical Farm design, color-coded according to the corresponding system.

Other options could have been to focus entirely on crop cultivation, to combine it with poultry or pig farming, or even to combine all three disciplines: crop cultivation, farm animal production and fish farming. 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. Derived from the space sector, the term open loop indicates that there is limited recycling and re-use of resources, whereas a closed loop system will attempt to recover resources when possible.

The trade-off between open loop and closed loop is based on the relative complexity and the potential cost savings. For the CE-study it was decided to look into a more or less closed loop system. Inedible biomass resulting from the crop cultivation is used as feed supplement for the fish, while the waste produced by the fish can be used as a source of nutrients for the crops. Due to the relative simplicity of fish farming compared to farm animal production, it was decided to investigate the possibility of fish farming in the Vertical Farm, rather than breeding farm animals. In Chapter 13.1, the impact of removing the three Fish Farming Floors from the building on the economic feasibility of the Vertical Farm is presented.

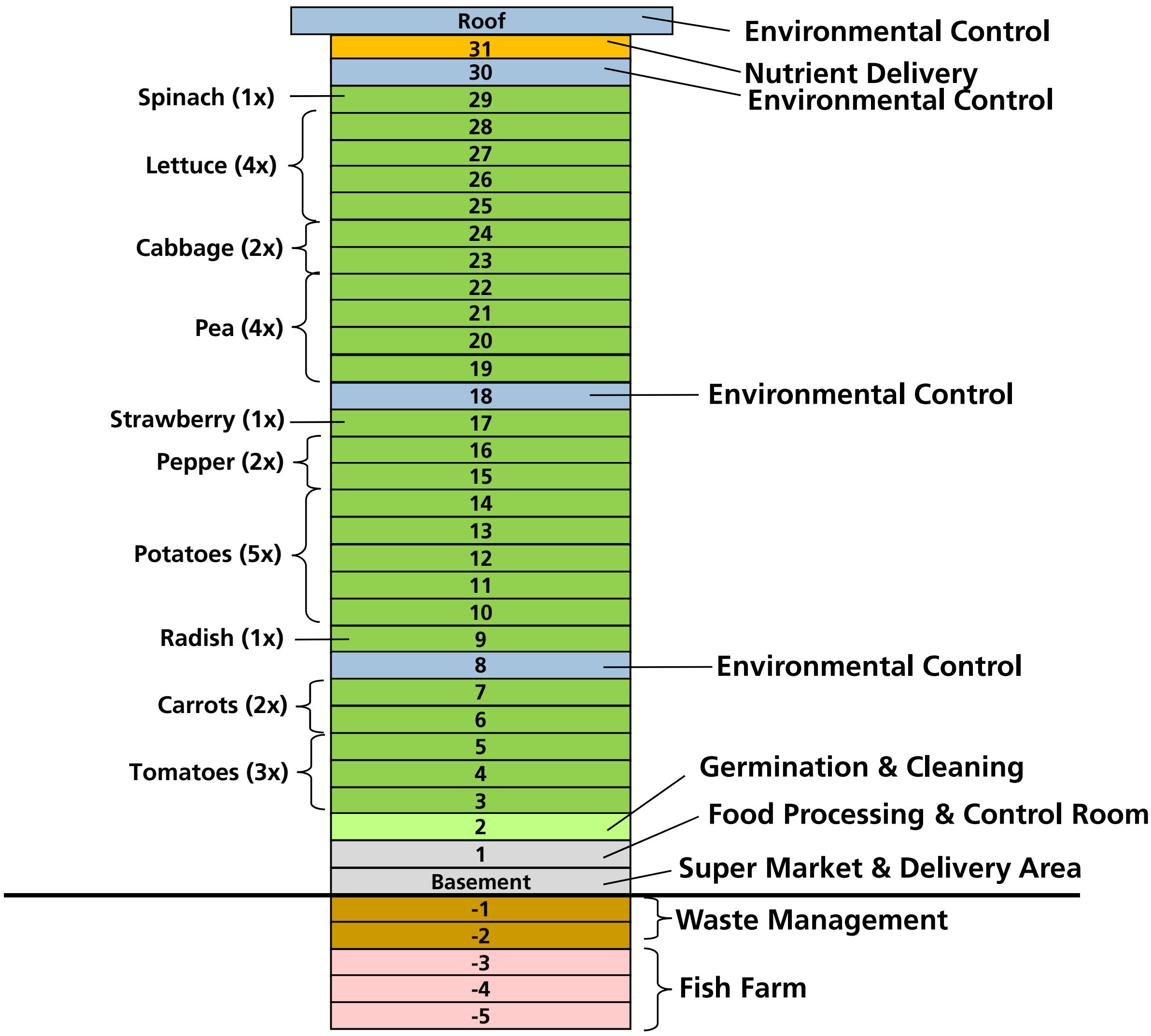


Figure 11: Vertical Farm floor distribution

Another aspect of the 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.

In the closed loop system, however, inedible biomass of the crops and fish are used to the fullest extent possible for nutrient extraction as well as biogas production for power generation and heating. Furthermore, waste water from the fish farms can be used for plant cultivation as irrigation supplement. Additionally, water evapotranspiration by the plants is recovered by dehumidifying the air. However, in Chapter 13, three scenarios are examined to determine the impact of closing the (resource) loops on the design and feasibility of the VF.

Another trade-off was made between mono- and multi-crop production. Mono-crop production means the Vertical Farm only produces one type of crop (e.g. Lettuce). 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. The complexity of the mono-crop design would be lower as well, since the same conditions (e.g. lighting, nutrient solution) can be used on every Plant Cultivation Floor.

On the other hand, the multi-crop production strategy, where the Vertical Farm produces several types of crop, would be better suited to meeting the dietary needs of a population. While in the future, a single city block may contain several Vertical Farms, each most likely dedicated to the production of one crop specie to maximize production, the CE-team decided that (as a show case design of Vertical Farms) it would be better to investigate the multi-crop strategy. The impact of switching from mono- to multi-crop production, and hence also the feasibility, of the Vertical Farm is too large to allow for an easy comparison of the two scenarios. Nevertheless, Chapter 13.4 shows a rough calculation of the possible crop yield of the Vertical Farm in case of mono-crop production.

The ten crops, which are selected for the CE-study, were chosen based on the availability of data, such as the plant growth period, the daily water uptake and the output of edible and inedible biomass. Each crop type was assigned an arbitrary number of floors, regardless of the expected demand.

Finally, a trade-off between natural and artificial illumination was carried out. The main factors are the potential energy- and 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.

It was decided to use only artificial lighting (LED) in the Vertical Farm. This decision was made based on several reasons, such as the ability to specifically tailor the lighting spectrum and lighting duration to suit the needs of each crop species, which can maximize yield by shortening the plant grow cycle. Another reason for artificial lighting is that natural lighting would only be able to illuminate the plants close to the outer windows of the building, unless complicated and expensive systems are used to move the plants or transport the sunlight deeper into the building. Also, the fact that no location was selected for the Vertical Farm was a reason to select artificial lighting. 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.

While it was unavoidable to base certain cost data for some of the cost estimations 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 e.g. Berlin or Tokyo.

3 Superstructure

As can be seen in the N^2-chart in Figure 10, there are interfaces between the superstructure and the other subsystems of the Vertical Farm. The footprint area, the number of floors and the total building height are just a few of the parameters, determining the costs and possible output of the Vertical Farm.

3.1 Assumptions

The following assumptions were made for the design of this (sub-)system:

- 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.
- Two meters on all sides of the building are reserved for ducts and structural elements
- The floors, walls and other structural elements are made of reinforced concrete
- No precautions against fungi, bacteria and other unwanted organisms are taken into account in the building design. It may be necessary to consider counter-measures (e.g. airlocks) to prevent or contain diseases in the Vertical Farm. This will be left for future studies.

3.2 Dimensions

Pre-CE work for the Vertical Farm assumed a cylindrical building, since it was believed that this would give a more even exposure to sunlight throughout the year. However, at the beginning of the CE-study it was decided that plant cultivation would be done using only artificial light. Because of this, the base of the building was changed to a square to allow for more efficient use of the floor space. Figure 12 shows the outer and inner structure of the Vertical Farm.

Based on requirements from other subsystems, the dimensions of the base changed several times. The final dimensions were selected to be 44 by 44 meters for the exterior structure. Only the inner 40 by 40 meters were available to the domain experts for their design calculations, while the remaining two meters on all sides are reserved for structural elements and air ducts leading from the Plant Cultivation Floors to the Environmental Control Floors.

An initial estimate for the total number of floors in the building resulted in a value of 30, of which 25 are assigned to plant cultivation. Upon researching and calculating the required equipment and floor area, it was found that more floors were needed for the other subsystems. Thus, keeping the number of plant grow floors at 25, the total number of floors in the building grew to 37. Aside from the Plant Cultivation Floors, there are three Fish Farming Floors, two Waste Management Floors, one Nutrient Delivery Floor, three Environmental Control Floors, one Germination Floor, one Food Processing Floor and one Supermarket & Delivery area on the ground floor. The floor distribution can also be seen in Figure 12.

From the total number of floors it was possible to determine the total height of the building. For this, a floor to ceiling height, as well as a floor to floor height was needed. Reference data on skyscrapers from around the world was found from [3] and can be seen in Table 3.

It was decided that the building for 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, which is within the range found from Table 3, leading to a floor-to-floor height of 4,5 meters.

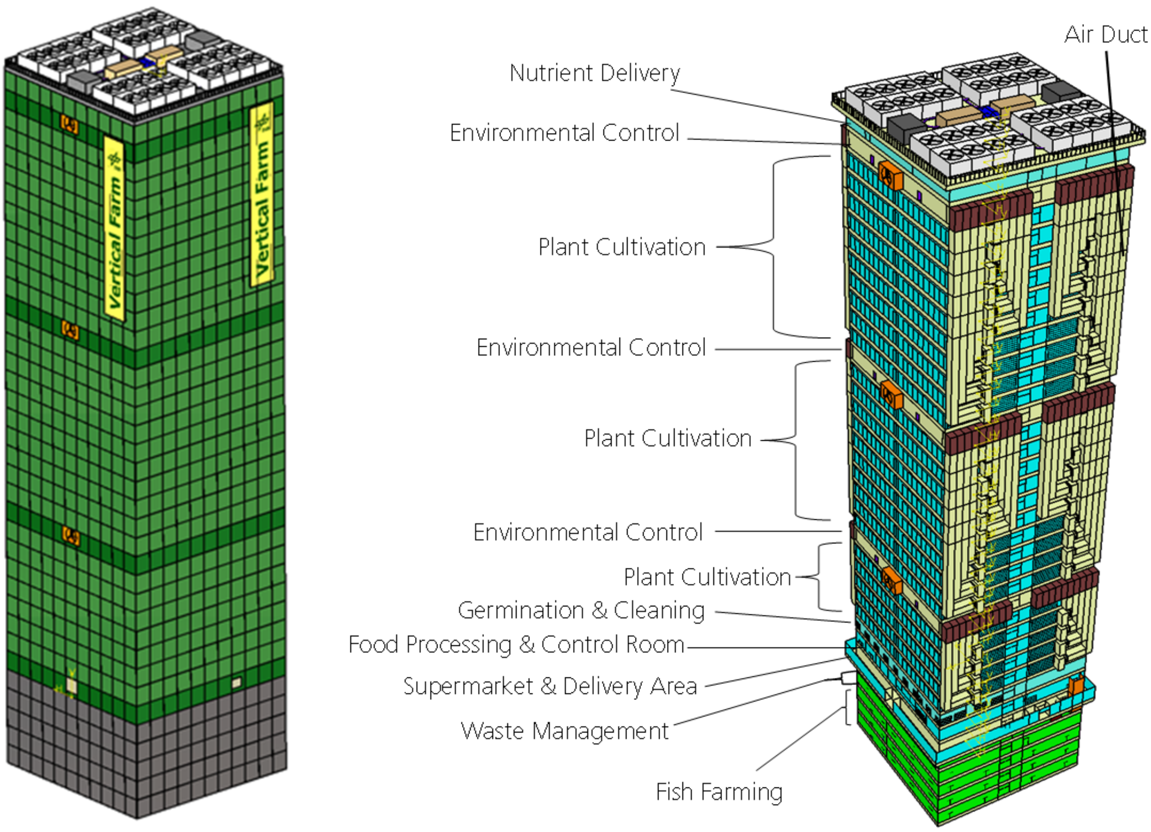


Figure 12: Outer and inner structure of the Vertical Farm

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 (with 5 floors beneath the ground level).

Table 3: Leasing depth, floor-to-floor and floor-to-ceiling heights of sample buildings from around the world [3]

Name of building	Leasing Depth [m]	Floor-to-floor height [m]	Floor-to-ceiling height [m]	Structural floor material
Taipei 101 T.	13,9 – 9,8	4,20	2,80	Composite
Shanghai WFC	12,5	4,20	2,75	Composite
Petronas T. 1-2	13,0 – 8,3	4,00	2,65	Composite
Sears Tower	22,9	3,92	2,70	Composite
Jin Mao Tower	14,8 – 11,8	4,00	2,79	Composite
Two International Finance Center	14,5	4,00	2,70	Composite
CITIC Plaza	11,3	3,90	2,70	Composite
Shun Hing Square	12,5 – 12,0	3,75	2,65	Composite
Central Plaza	13,5 – 9,4	3,90	2,60	Reinforced concrete
Bank of China	17,6	4,00	2,80	Composite
Average	**12,1**	**3,98**	**2,7**	

3.3 Design elements

A total building height of 167,5 meters, with a length (and width) of 44 meters, gives an aspect ratio (height to width 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 for example, it does mean that the structural design can be rather straightforward. From [4] it can be found that for aspect ratios of seven 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 [5], specific dimensions for the stairwell could be determined. Nevertheless, it has to be stated that the VF is not an office building or apartment complex which should be capable of evacuating hundreds or thousands of people. The Vertical Farm will have around 60 employees (see Chapter 12.3.3) and perhaps some dozen people in the Supermarket and Delivery Area.

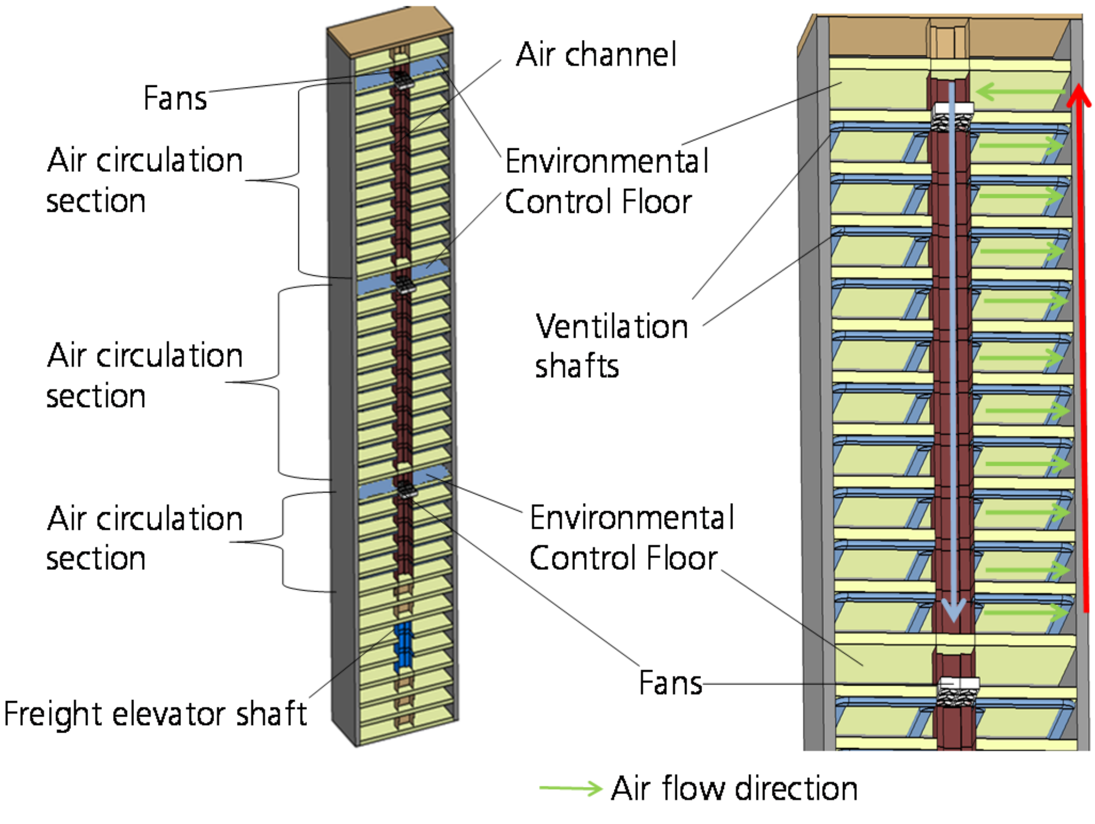


Figure 13: (Left) Section view of the inside of the Vertical Farm. (Right) Diagram of the Vertical Farm airflow

For simplicity reasons, it was assumed 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 center 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 13 (left).

Following some design iterations it was determined that one floor for the environmental control system would not be enough (to fulfil closed-loop design). Instead three floors were needed, with each of the floors maintaining the required air quality for eight or nine Plant Cultivation Floors. The Environmental Control Floors (ECF) ensure that air flows down to the Plant Cultivation Floors through a large air channel running through the center of the building into the Plant Cultivation Floors, where it is guided into the Grow Units through air ducts, see Figure 13 (right).

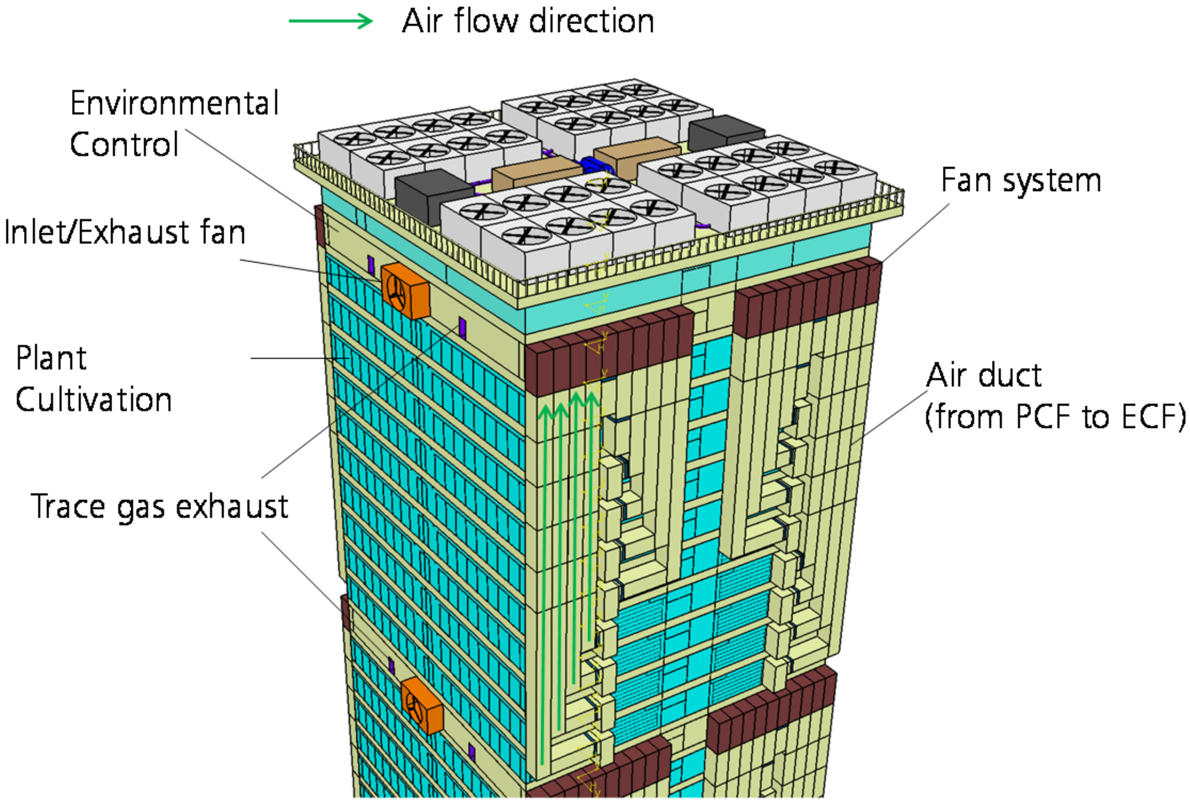


Figure 14: Section view of air inlets, outlets and ducts

Air flows down this channel and Fans are used to ensure air flows over the plants at the proper rate to maintain the desired air quality (e.g. active CO_2 injection). Then, after passing through the Grow Units, the air flows into a central duct which leads the air out into ducts at the sides of the building. There the wet 'used' air flows back up to the Environmental Control Floor for processing. The ECF also regulates the air exchange between the VF and the outside, like for example inlet/ exhaust of air & trace gas exhaust (see Figure 14).

3.4 Building cost analysis

The building costs are displayed in chapter 12.2 (Non-recurring costs)

4 Germination Floor

The start of the plant life cycle is the germination phase, during which the first plant sprouting from seeds occurs. To ensure successful germination of the vast amount of plants and to shorten the actual time in the PCFs, it is necessary to have a separate Germination Floor.

4.1 Assumptions

Certain assumptions were made during the design study and the relevant ones for the Germination Floor are listed below:

- It is assumed that a minimum of 75 Grow Lids, along with associated lighting and nutrient delivery system, can be stacked vertically inside one Germination Unit.
- It is assumed that the length and width of a Grow Lid are one meter.
- It is assumed that the germination phase is significantly shorter than the remainder of the crop life cycle.

4.2 System Description

The general plant cultivation approach, which will be used for the Vertical Farm, consists of Grow Lids and Grow Pallets. The Grow Lid holds the plant stem and divides the root- from the shoot zone. For each plant type there will be a customized grow lid, where the spacing of the plant holders are individual designed accordingly to the morphological grow parameters of the specific plant types (see Figure 15).

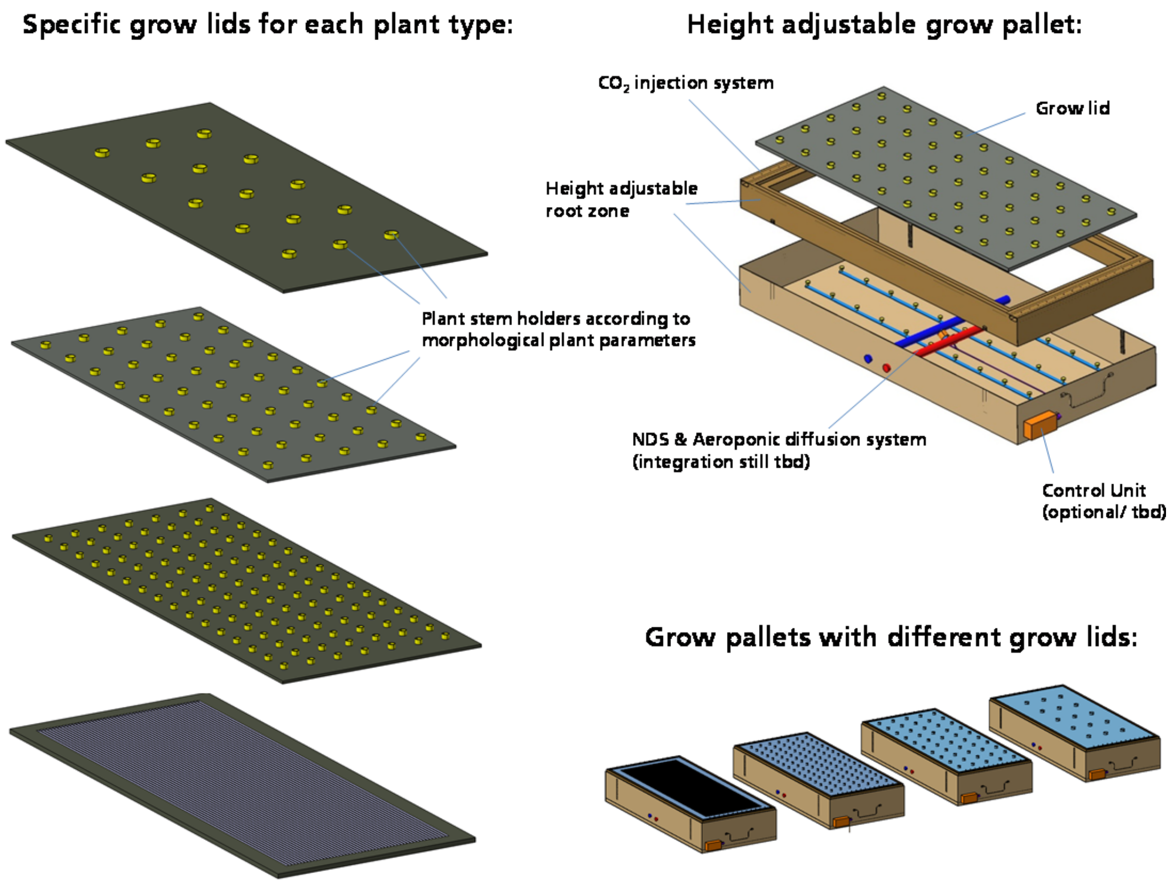


Figure 15: Initial design of the Grow Lid with according Grow Pallet systems. (Note: Picture does not reflect the exact chosen Grow Lit dimensions of 1 x 1 m)

The root zone is within the grow pallet. The grow pallet is standardized, which means it shall be suitable for all plant types (one size fits it all). Therefore, it can be adjusted in height to fit the root zone requirements of the plants. Furthermore, the Grow Pallet comprises of aeroponic diffusion system, CO_2 injections tubes (optional, still tbd) and plant health sensors (optional, still tbd). An optional design of the Grow Pallet/ Grow Lid was made with respect to the accommodation of the NDS within the Grow Lid itself (see Figure 16). Future studies need to evaluate the best design solution on this issues.

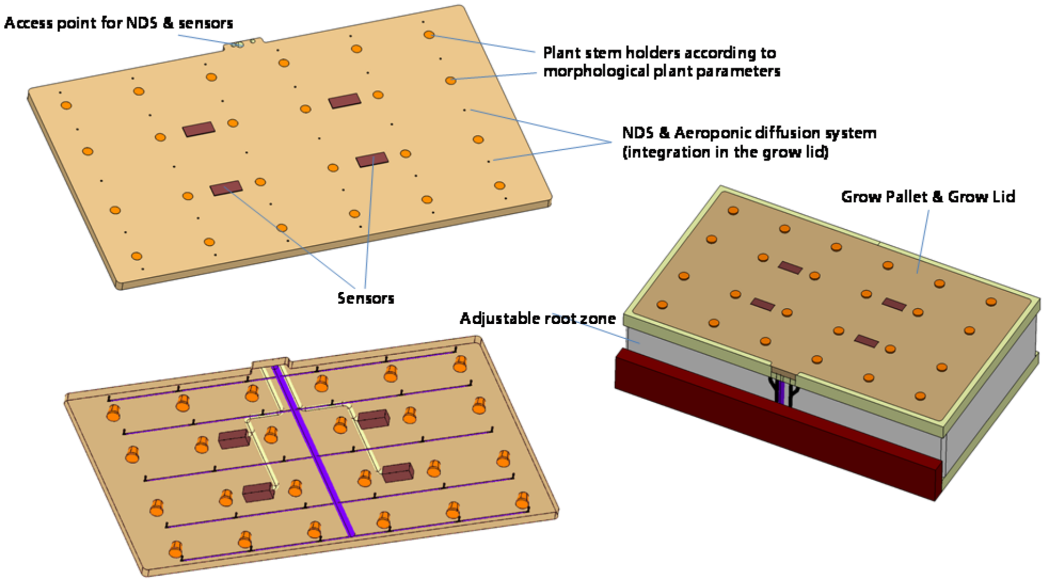


Figure 16: Optional design of a Grow Pallet with according Grow Lid

During the CE-study also other plant/ root zone accommodation approaches were evaluated, where for example the NDS is decoupled from the Grow Pallets in total. This way the complexity and the single point failure probability can be increased. Further investigations will need to evaluate this approach as well. Also other options, where the total abandonment of the grow pallet approach was considered and evaluated, but are not displayed in this report. Nevertheless, the Grow Lid/ Grow Pallet approach allows to jump start the seed formation process within a germination unit and only place the Grow Pallets (incl. sprouts) in the cultivation floors when the plants are ready for the photosynthesis. This way the overall production cycle can be shorten. Furthermore, harvest- and cleaning procedures are easier to perform with the modular Grow Pallet/ Lid approach.

Figure 17: Examples of seed pads for plant support [Source: AgriHouse, Inc.]

A Grow Lid is envisioned as a rigid structure with a number of openings which can hold nets or pads acting as support for plants throughout the cultivation cycle (see Figure 17). During the germination phase of the plant life cycle, the Grow Lids will be placed in Germination Units, where the desired lighting conditions and nutrient solution quantities will be provided to ensure successful sprouting (depending on crop type: warm & wet; optional initial light)

Once the initial plant growth has occurred, the Grow Lids will be removed from the Germination Units and placed on top of Grow Pallets. These Grow Pallets are essentially containers, providing additional structural support, but also ensuring an enclosed root zone which is shielded from the grow light to ensure further root growth. Additional sensors, as well as the necessary piping and cabling, will be present to ensure that all the relevant data is collected. Last but not least, the Grow Pallet is designed to facilitate the recovery of any nutrient solution which is not absorbed by the plant roots.

Once the Grow Lids are placed on the Grow Pallets and all interfaces between the two have been properly checked, the combined structure is moved from the Germination Floor to one of the Plant Cultivation Floors where it is placed in a Grow Unit. A Grow Unit, similar to the Germination Units, contains the necessary components to achieve and maintain desired conditions for the plants (e.g. lighting, air and nutrients). A more detailed description of the Grow Units is given in the next chapter, which covers the design of the Plant Cultivation Floors.

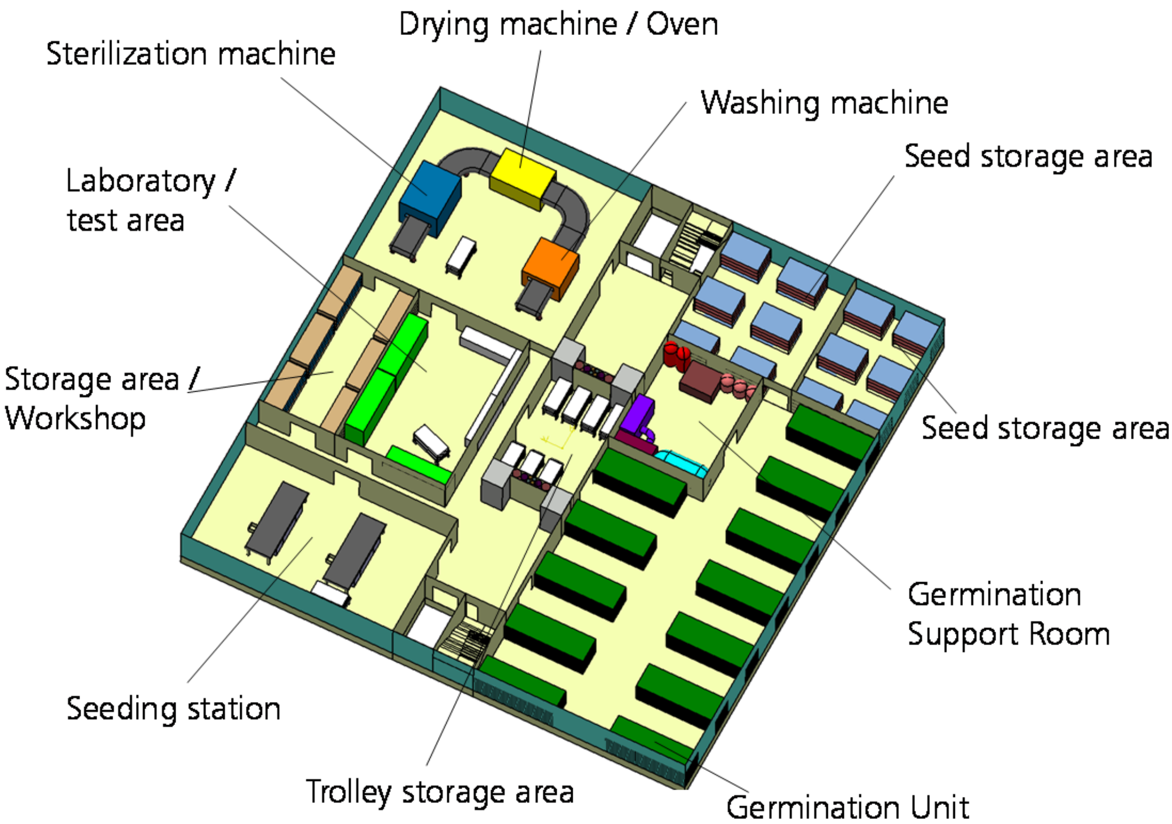


Figure 18: Germination Floor design

The Germination Floor, as shown in Figure 18, contains 12 Germination Units. Each Germination Unit is 6,25 meters long, 2 meters wide and 3 meters high. Using the assumptions made on the space required for the Grow Lids, it is possible to determine that one Germination Unit can hold at least 900 Grow Lids at a time. Thus, the twelve Germination Units combined would be able to hold a minimum of 10.800 Grow Lids. Each Grow Lid will contain several seeds, with the exact amount depending on the crop species, leading to a total capacity of the Germination Floor of several tens of thousands of plants/ sprouts.

Taking into account that the germination phase is significantly shorter than the rest of the plant life cycle, several batches of plants can be germinated during one plant cultivation cycle. As such, it is estimated that twelve Germination Units should be able to supply sufficient seeds for the Plant Cultivation Floors to operate at full capacity. If future studies should show that this is not the case, then there is still enough room on this floor to increase the number of Germination Units.

In order to maintain optimal conditions for seed germination, there is a support room, which houses the nutrient- and water tanks, along with some pumps and heat exchangers for the Germination Units. This room also controls the conditions in the Germination Units, ensuring that the seeds are kept at the required environmental conditions.

Aside from the Germination Units, there are two rooms for seed storage. These two rooms can 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.

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 Lids at predetermined distances.

Last but not least, the floor has another storage/ workshop room, a laboratory area to take and analyze samples from the entire building 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 seeds and plant specimens can be examined, while the cleaning area is present to clean equipment, most importantly the Grow Lids and Grow Pallets, and prevent contamination and sources of disease from getting in contact with the plants.

4.3 Equipment List

The Germination Floor needs to germinate enough seeds to allow the 25 Plant Cultivation Floors to run at full capacity. Additionally, it needs to clean all the equipment used in seeding, growing, harvesting and processing of the plants. To achieve this, certain equipment needs to be present in the Vertical Farm.

It is possible to determine the total set-up cost of this equipment, by creating a list of required equipment and estimating the cost. This is done for the Germination Floor in Table 4. Cost estimations are done based on a best engineering estimate approach. The cost of the required Grow Lids and Grow Pallets are taken into account in the next chapter, which discusses the Plant Cultivation Floors.

Costs are estimated to be higher than comparable existing equipment as it is likely that most of the equipment will be custom designed to match the VF needs. The cost estimations do not take into account the cost reductions which are likely to result from mass scale effects. Standard equipment for buildings, such as lighting, fire safety equipment and harnessing is taken into account in the cost estimation of the building, which is described in Chapter 12.2.

Table 4: Initial cost estimation of the Germination Floor equipment [FY12]

Equipment	Units [-]	Price [€/unit]	Total [k€]
Sowing machines (including spares)	4	40.000	160
Washing machine (including spares)	2	30.000	60
Drying machine / Oven (including spares)	2	30.000	60
Sterilization machine (including spares)	2	50.000	100
Germination Units	12	30.000	360
Water tanks	3	5.000	15
Nutrient tanks	3	5.000	15
Water buffer tank	1	2.000	2
Pump (including spares)	3	10.000	30
Heat exchanger	1	50.000	50
Storage cabinets	20	1.000	20
Trolleys	50	500	25
Lab equipment	1	1.000.000	1.000
Work space / desks	3	1.000	3
Workshop equipment	1	100.000	100
Total set-up costs			**2.000**
Margin of 20%			**400**
Total set-up costs with 20% margin			**2.400**

5 Plant Cultivation

The crop selection and design of the plant growth platforms is critical w.r.t. the output of the Vertical Farm. In this chapter the crops which have been selected for cultivation are discussed. Additionally, the design of the Plant Cultivation Floors is discussed and calculations are performed to obtain an estimate of the total edible biomass and total inedible biomass produced.

The output data can ultimately be used to give an initial estimate for the cost of food grown within the Vertical Farm. An initial estimate of inedible biomass can also be used by the waste management to appropriately plan the corresponding floor area and equipment for its tasks.

5.1 Assumptions

Certain assumptions were made during the design study and the relevant ones for the Plant Cultivation Floors are listed below:

- It is assumed that the reference data from the NASA baseline values and assumptions document [6] is accurate for hydroponic plant cultivation at optimal conditions with enhanced CO_2-levels, as is typical for NASA studies of Advanced Life Support (ALS) crops [7].
- The root zone heights and the minimum plant spacing distances for the used VF crops have been assumed.
- According to literature [8, 9], aeroponic plant cultivation allows for an increase in yield of up to 70 - 80% with respect to hydroponic plant cultivation. Taken into account that the yield increase is likely dependent on the crop species, and taking a conservative estimate, a factor of 1,4 is therefore assumed, to take into account the increase in edible biomass production due to the use of aeroponics rather than hydroponics.
- A minimum of 10 cm is required per Grow Channel to accommodate the LED panels and structure and to allow for some space between the lighting and the plant canopy.
- The plant growth period for the crops on the Plant Cultivation Floors will be shorter than the values given in [6], because the seeds are already germinated when placed in the Grow Units. Furthermore, with optimized lighting the growth periods can be shortened even more. The shorter growth periods would lead to an increase in biomass yield. Nevertheless, for the calculations in this study these facts were not taken into account so that some additional hidden margins are created.
- The number of Plant Cultivation Floors assigned to each crop species was assigned arbitrarily.
- The potential yield is based on a full production phase; So no initiation phase is considered.

5.2 Crop Selection

A list of 10 plants (shown in the first column) was chosen for calculation of yields produced in the Vertical Farm building. Criteria for selection were availability of parametric data for cultivation and yield in artificial environment and a relatively high biomass output, as mentioned in Chapter 2.2. Table 5 gives the critical parameters in the scope of plant growth platform subsystem for the VF crops.

Initially soybean was selected as one of ten plant candidates, but the edible biomass yield was very low in comparison with the other plants. The team decided to replace the soybeans with strawberry which produces a better yield within the Vertical Farm. Peas also have a relatively low edible biomass yield, but have been kept as one of the Vertical Farm crops, as it is quite common in the average person's diet.

Table 5: Plant parameters [6]

Crop	Shoot zone height [m]	Root zone height [m]*	Fresh edible biomass [g/m²*day]	Fresh inedible biomass [g/m²*day]
Lettuce	0,25	0,15	131,35	7,30
Cabbage	0,35	0,15	75,78	6,74
Spinach	0,25	0,15	72,97	7,30
Carrots	0,25	0,30	74,83	59,87
Radish	0,20	0,30	91,67	55,00
Tomatoes	0,40	0,20	173,76	127,43
Peppers	0,40	0,20	148,94	127,43
Potatoes	0,65	0,40	105,30	90,25
Peas	0,50	0,20	12,20	161,00
Strawberry	0,25	0,15	77,88	144,46

* The parameters in this column are not based on the NASA baseline values document [6], but are estimated by the CE-team.

5.3 System Description

The Vertical Farm contains a total of 25 Plant Cultivation Floors. The floor layout for each Plant Cultivation Floor is the same, regardless of the crop species being cultivated. The seed germination was previously discussed, with the germinated Grow Lids being attached to Grow Pallets before being delivered to the Plant Cultivation Floors and placed in Grow Units.

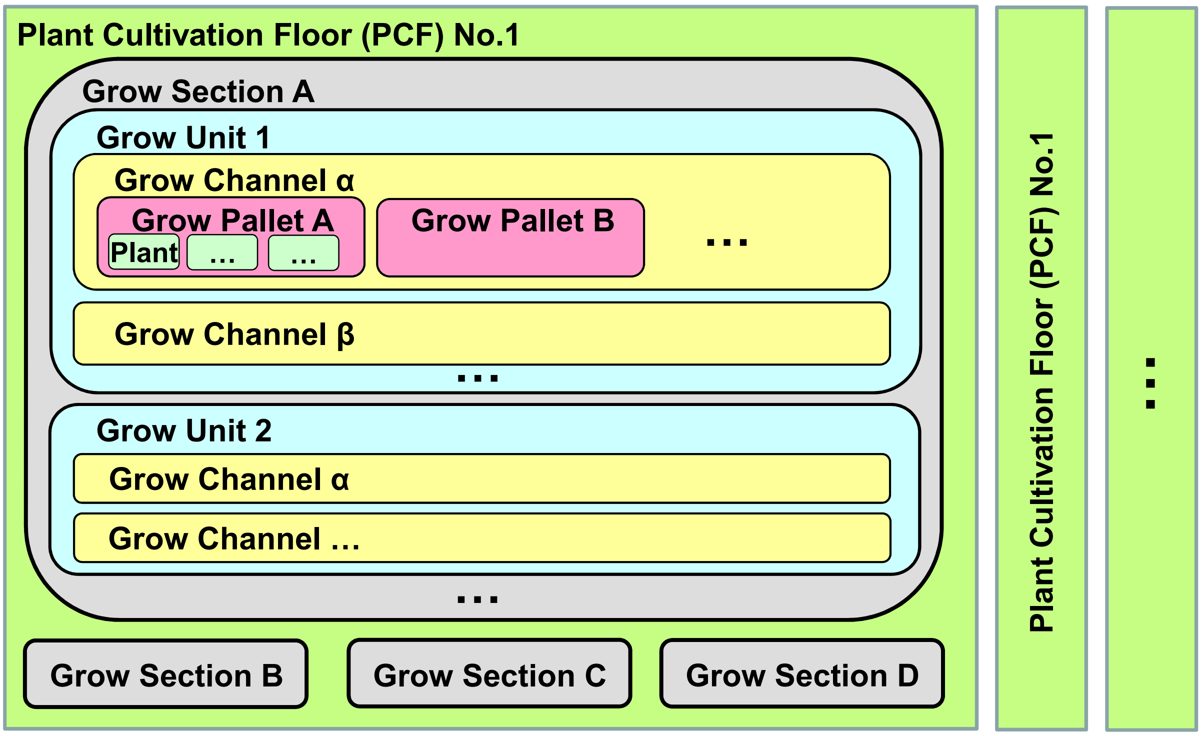


Figure 19: Systematic breakdown of one Plant Cultivation Floor with its four grow sections A-D.

There are four growing sections (A-D) on each Plant Cultivation Floor and every section consists of 19 Grow Units (compare systematic breakdown Figure 19). The Grow Units for the plant growth are comprised of four fixed platforms in the corners of each section and 15 moving platforms. The moving platforms have a footprint area of 14,5 m² (7,25 m x 2 m) and the fixed platforms 7,25 m² (7,25 m x 1 m).

Depending on the crop species which is being grown on the specific Plant Cultivation Floor, a Grow Unit may hold more or fewer Grow Pallets, leading to different overall grow areas for the floors. The maximum number of Grow Pallets which can fit inside a Grow Unit is calculated by dividing the height of a Grow Unit (3 meters) by the sum of the shoot and root zone height of the plants with an added ten centimeters for the LED panels, structures and lighting-to-canopy spacing. The maximum numbers of stacks per Grow Unit ranges from two grow channels (e.g. potatoes) to six (e.g. lettuce, spinach and strawberries) grow channels.

The effective grow area per Grow Unit is the footprint area minus the area reserved for air management, nutrient delivery and power supply equipment and interfaces. This comes out at 13,5 m^2 for the moving Grow Units and 6,75 m^2 for the fixed Grow Units. Multiplying these numbers by the total amount of Grow Units per Plant Cultivation Floor yields an effective footprint area per floor of 918 m^2. The total available area per floor is 1.600 m^2, meaning that about 57% of the total footprint floor area of a Plant Cultivation Floor is used for plant cultivation.

In Figure 20, the floor layout for a Plant Cultivation Floor can be seen. For one of the sections of the Plant Cultivation Floor, the ducts have been removed to allow for a better look at the Grow Unit distribution within a section.

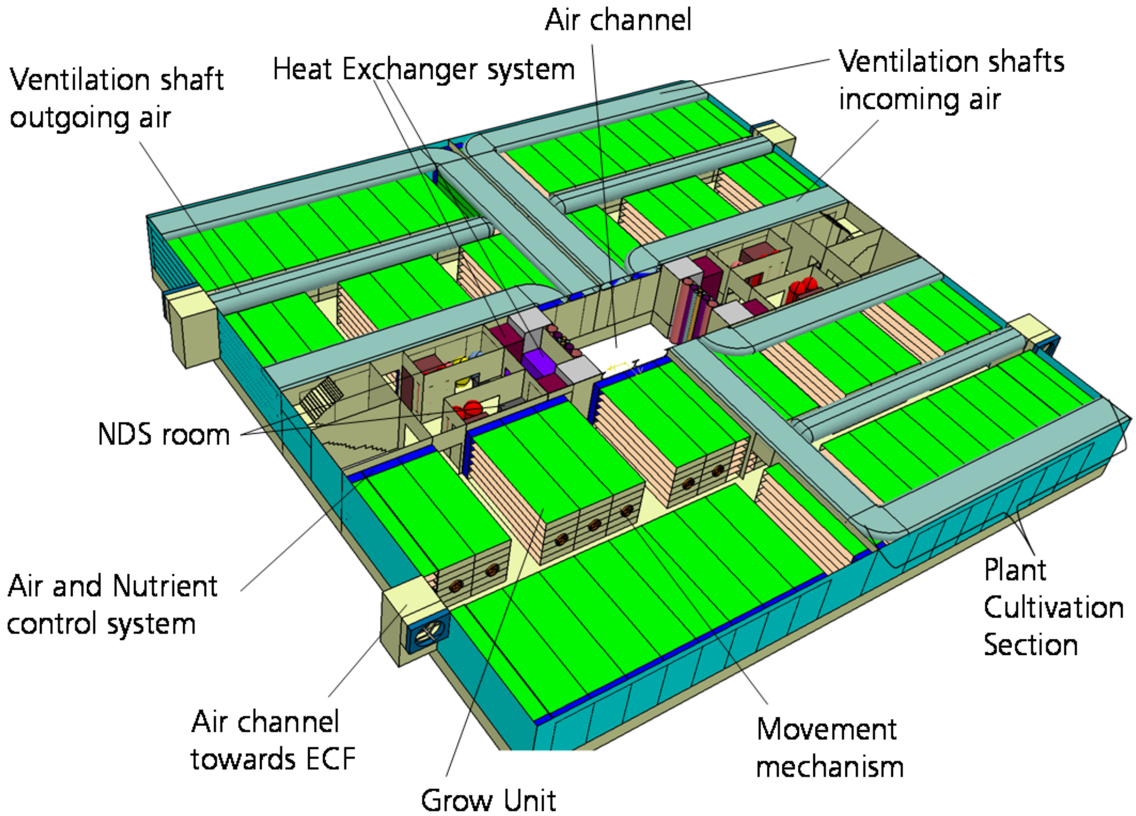


Figure 20: Plant Cultivation Floor design

The reason for using moveable platforms (grow units) is the additional gained grow space, which would otherwise need to be left open for servicing alleys. This increases the total number of Grow Units, and hence the total grow area. Using the moving mechanisms, the workers can still access each Grow Unit from the side for harvesting and maintenance purposes.

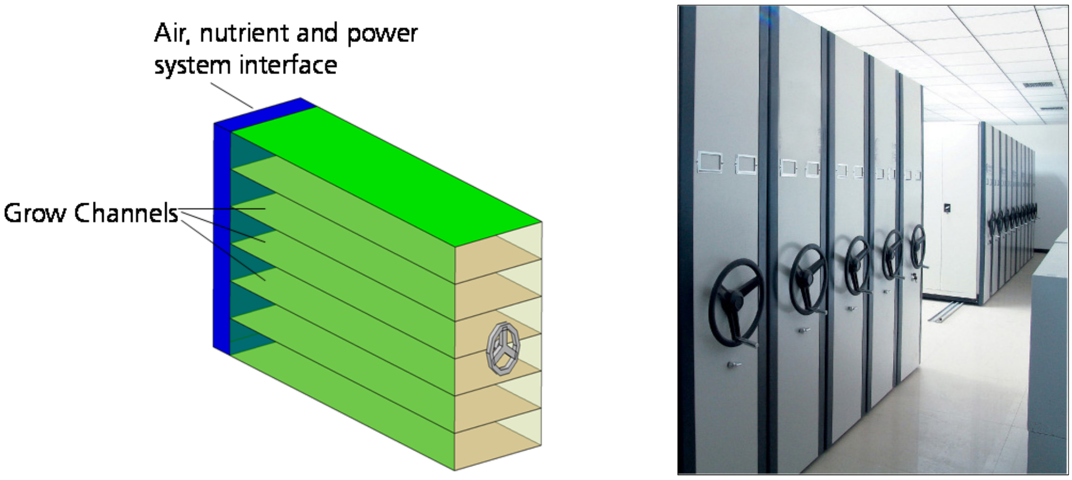


Figure 21: (Left) Close-up view of a moveable Grow Unit. (Right) Mobile Filing Cabinets [source: Simply International Industrial Ltd.]

Figure 21 (left) presents an initial close-up view of a moveable Grow Unit. The movement mechanism is envisioned to be similar to those used in archives, see Figure 21 (right). The blue section of the Grow Units is allocated space, which has been reserved for air management, nutrient delivery interface and power supply equipment.

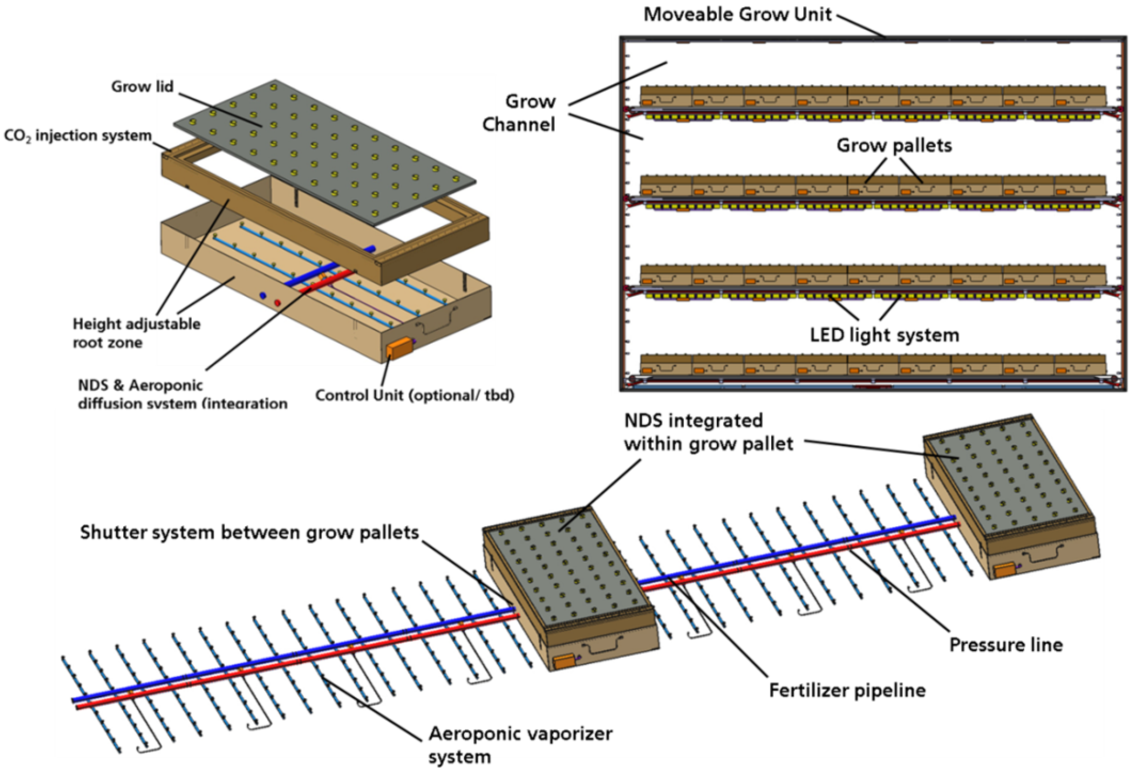


Figure 22: Left: Grow Pallet (dimensions on picture are not corresponding here calculated dimensions of 1m²); Right: Movable grow unit with the adjoining subsystems (e.g. NDS, CO_2 injection); Bottom: Aeroponic NDS within one grow channel

The grow unit comprises all necessary subsystems, needed for a porper plant cultivation (compare Figure 22). To spread out the crop biomass output, the start of the grow cycles for each section will be spaced several days or weeks apart, depending on the crop. This way, each section will also be harvested at a different time.

This results in lower output per harvest, but has the advantage of reducing the time between harvest events, where new fresh food becomes available. Future studies should create exact grow plans to optimize the (edible) biomass output of the VF.

Since each section is at any given time in a different part of the crop grow cycle, various conditions will be needed to ensure optimal growth. Therefore, each section will be independently controlled which allows workers to easily check and, if necessary, alter the baseline conditions for that section. Additionally, temperature, humidity and CO_2 sensors ensure that the actual conditions match the desired conditions.

Each section (A-D) has a dedicated nutrient delivery system. This can be seen in Figure 23, which shows a close-up (cut-out) view of the nutrient delivery system for two of the sections on a Plant Cultivation Floor. The nutrient delivery system rooms have small nutrient and water buffer tanks, a mix computer and a pump. Water and nutrients are delivered from the Nutrient Delivery Floor to the Plant Cultivation Floors where it is stored until it is needed.

Furthermore, per two plant growth sections there is one heat exchanger system which ensures that waste heat from the LED lighting system is transported away from the Plant Cultivation Floors and ultimately dissipated into the external environment, see Figure 23.

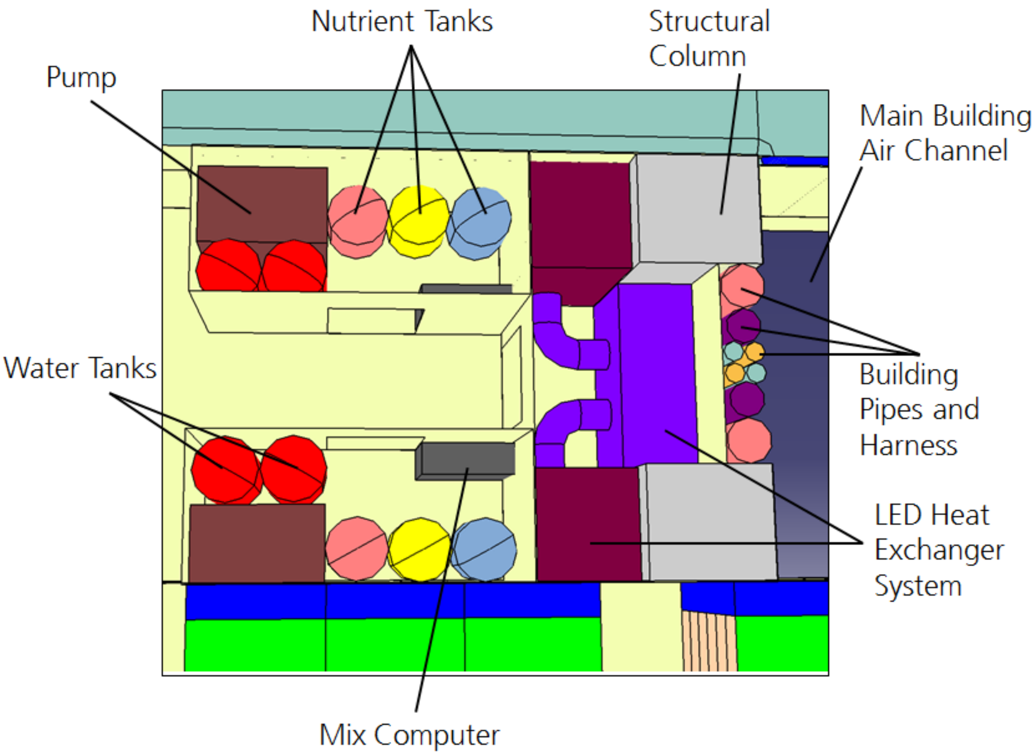


Figure 23: Close-up View of the nutrient delivery system and heat exchanger system on the Plant Cultivation Floors

As mentioned earlier (refer to Chapter 3.3) there is a main building air channel, through which air flows down from the Environmental Control Floors to the Plant Cultivation Floors. Using fans, the air is guided from this "main building air channel" into ventilation shafts running into the four sections of each Plant Cultivation Floor. These ducts run along the rows of Grow Units and allow air to flow into these Grow Units and towards the plants where the air can interact with the plants.

Waste air is forced out of the Grow Units into the center alley of the sections where it rises to enter an (output) air duct, which guides the waste air out of the Plant Cultivation Floor and back to the Environmental Control Floor.

5.4 Crop Yield and Waste Production

Based on the maximum heights of the crops and the illumination- and structure system requirements, it was possible to determine the maximum number of Grow Pallets, which can be stacked vertically in one floor. This information, along with the Plant Cultivation Floor layout, makes it possible to determine the total growth area per floor for each crop type.

It was found that the 25 Plant Cultivation Floors cover a total plant growth area of 92.718 m^2 (see Table 6). This is roughly 37 times larger than the footprint area (2.500 m^2) of the site on which the building is situated. The total growth area depends on the chosen plant types and on the number of floors assigned to each crop species. For example, 25 Plant Cultivation Floors dedicated to lettuce cultivation would allow for a total grow area of 137.700 m^2, while 25 floors of potatoes would only reach a growth area of 45.900 m^2. Also refer to chapter 13.4 (Trade-off mono-crop approach).

Table 6 lists parameters related to the growth area in the Vertical Farm for each crop. The second column gives information about the maximum number of grow channels (stacks) per Grow Unit for each plant type. Taking the fixed number of Grow Units per floor into account, one can calculate the total cultivation area per Plant Cultivation Floor (PCF) (see third column). This results into a total number of Grow Units in the VF (4-5 columns). Ultimately, the last column presents the total growth area per crop.

Table 6: Crop Growth Area

Crops	Maximum number of stacks (Grow Channels) per Grow Unit	Cultivation area per floor [m^2]	Number of PCF per VF	Total number of Grow Units	Total cultivation area per VF [m^2]
Lettuce	6	5.508	4	304	22.032
Cabbage	5	4.590	2	152	9.180
Spinach	6	5.508	1	76	5.508
Carrots	4	3.672	2	152	7.344
Radish	5	4.590	1	76	4.590
Tomatoes	4	3.672	3	228	11.016
Peppers	4	3.672	2	152	7.344
Potatoes	2	1.836	5	380	9.180
Peas	3	2.754	4	304	11.016
Strawberry	6	5.508	1	76	5.508
Total			**25**	**1.900**	**92.718**

Table 7 shows the biomass production calculations for the Vertical Farm. The second and third columns contain the fresh edible and inedible biomass yield for the crops using aeroponic growth systems. Inedible plant parts are a by-product to the edible biomass in crop cultivation. Inedible biomass is defined as the amount of biomass that cannot be processed for food production. These masses have to either be processed in internal composting and waste processing units, which is discussed in detail in Chapter 11, or the waste has to be transported to external devices.

The values in the second and third columns are calculated by multiplying the values from [6] by the aeroponic yield increase factor of 1,4. From [7] it was found that the data which can be found in [6] is most likely for hydroponic plant cultivation with elevated CO_2 levels. Then, from [8, 9] it was found that aeroponic plant cultivation can increase biomass yield by up to 70 - 80% with respect to hydroponic plant cultivation. For a first (conservative) study, a yield increase factor of 1,4 was selected.

Table 7: Aeroponic biomass production calculations

Crops	Fresh edible biomass yield with aeroponics [g/m²*day]*	Fresh inedible biomass yield with aeroponics [g/m²*day] *	Total Growth Area [m²]	Fresh edible biomass yield per VF with aeroponics [tons/year]	Fresh inedible biomass yield per VF with aeroponics [tons/year]
Lettuce	183,89	10,22	22.032	1.478,78	82,18
Cabbage	106,09	9,44	9.180	355,49	31,61
Spinach	102,16	10,22	5.508	205,38	20,55
Carrots	104,76	83,82	7.344	280,83	224,69
Radish	128,34	77,00	4.590	215,01	129,00
Tomatoes	243,26	178,40	11.016	978,12	717,33
Peppers	208,52	178,40	7.344	558,94	478,21
Potatoes	147,42	126,35	9.180	493,96	423,36
Peas	17,08	225,40	11.016	68,67	906,30
Strawberry	109,03	202,24	5.508	219,2	406,60
Total			**92.718**	**4.854,37**	**3.419,84**

* Parameters from [6] and yield increase factor of 1,4 already included

The fourth column of Table 7 contains the total growth area per crop as calculated in Table 6. Using the data from the second, third and fourth columns it was possible to calculate the fresh edible and inedible biomass yields of the Vertical Farm crops per year, using aeroponic growth systems. These values are listed in the fifth and sixth columns of Table 7.

The edible biomass output per year is the average expected output for the Vertical Farm. It does not take into account that the yield will be lower in the first year due to the initial start-up phase of the plant cultivation cycles. In other words, the calculated biomass output is for full operation mode. However, yield may differ slightly from year to year depending on whether harvesting dates fall at the end of a calendar year or at the beginning of a year.

Taking into account a yield increase factor of 1,4 due to the performance increase of aeroponics over hydroponics, a total yield (edible plant biomass) of 4.854 tons/year was calculated for the whole building. Furthermore, it was calculated that the Vertical Farm yields 3.420 tons/year of inedible crop biomass.

The data in Table 7 is based on the assumption that the entire crop biomass is removed during harvest. As such, values may differ significantly if other harvesting strategies are employed. Additionally, the values presented are expected averages, as mentioned previously.

5.5 Equipment List

It is possible to determine the total set-up cost for the interior of these floors, by creating a list of required equipment and making a best estimate for the cost. This is done for the Plant Cultivation Floors in Table 8. Total costs are given in k€ (FY 2012) and are rounded.

Table 8: Initial cost estimation for Plant Cultivation Floor equipment [FY12]

Equipment	Units [-]	Price [€/unit]	Total [k€]
Fixed plant Grow Units	400	5.000	2.000
Moveable plant Grow Units	1.500	10.000	15.000
Grow Pallets	110.000	25	2.750
Grow Lids	110.000	5	550
Seed Pads	2.500.000	1	2.500
Control Units	100	250	25
Thermostats	300	50	15
Air condition and humidity sensors	300	50	15
CO_2 sensors	300	100	30
Total set-up costs			**22.885**
Margin of 20%			**4.577**
Total set-up costs with 20% margin			**27.462**

Note that the duct system for the air management is separately calculated within the Environmental Control Floors (see Chapter 9). LED panels and heat exchangers are calculated within the light domain (chapter 8) and the nutrient delivery components are calculated within chapter 7 (nutrient delivery).

6 Fish Farming

As discussed previously, the Vertical Farm will contain three floors dedicated to the production of fish. The fish farms are used to close essential resource loops. Waste water from the fish can be used as fertilizer supplement for plant cultivation and plant waste can be used as food supplement for the fish. The combined process of fish farming and plant cultivation is also known as aquaponics and is illustrated in Figure 24 (left).

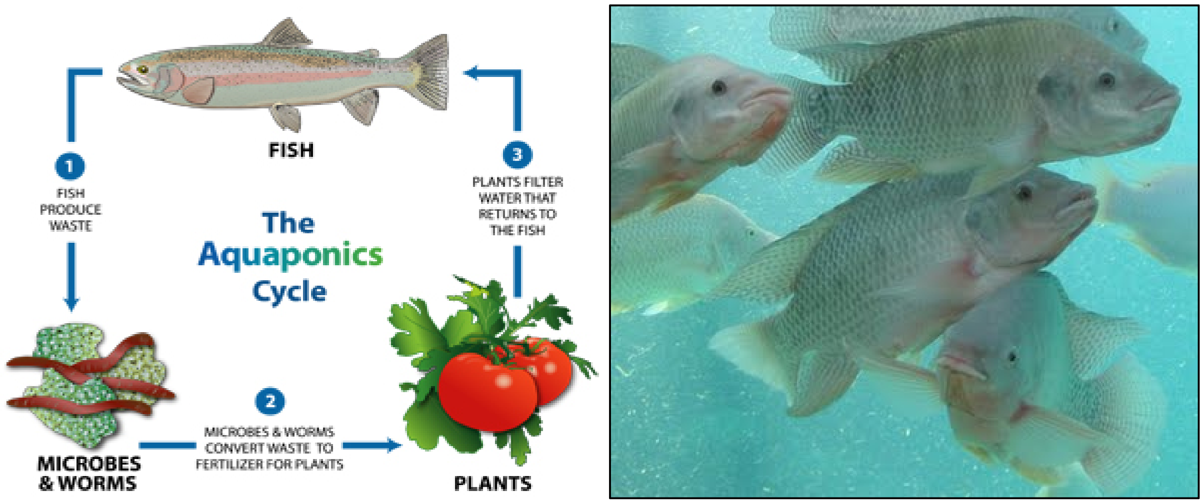


Figure 24: (Left) Aquaponics cycle. (Right) Tilapia fish

6.1 Assumptions

Certain assumptions were made during the design study and the relevant ones for the Fish Farming Floor are listed below:

- The fish yield calculations are based on a full production phase, meaning that it does not consider the initiation phase of the fish farms, during which fingerlings are first introduced into the tanks.
- It is assumed that the tilapia fish feed consists of 1 ton of inedible plant biomass from the Vertical Farm and the remainder of the required fish feed is high-protein fish feed which is bought from an external source.
- It is assumed that the waste water in the Fish Farming system is recycled. The nitrate-rich (waste) water can be used as fertilizer supplement for the plants. Nevertheless, this option has not been investigated further (only mentioned as one option) and is a subject for future studies, since it can further close the material loops within the VF and so contribute to a more sustainable urban agriculture.
- For the design of the fish farm, it is assumed that the fish in each of the growth stages would be in separate tanks from the fish in other growth stages. To ensure a steady state production, each growth stage has the same daily output of 'mature' fish.
- It is assumed that a small floor section is foreseen for the breeding of some fishes in order to generate fish spawn (not analyzed in present study). Eventually fish spawn is bought from external sources.

6.2 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 (shown in Figure 24 (right)) is chosen because of the following properties:

- **Feed** – Tilapia is able to consume a wide range of feed, which makes it very adaptable to a Vertical Farm since a large part of the required fish feed can be made from inedible plant biomass.
- **Water temperature** – The tropical water temperature required by tilapia is ideal for a Vertical Farm as heat runoff 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 2,0 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

Unfortunately, low levels of omega-3 and high levels of omega-6 make the fish relatively unhealthy, compared to other fish.

6.3 System Description and Fish Yield

The design of the fish farm is based on a balanced production cycle, which aims to optimize the production between the maturity stages and corresponding tanks.

The Fish Farming Floor consists of five tank sizes, for a total of 16 tanks per fish floor. The first three growth stages of the Tilapia fish are grown in 'growout' tanks, which have a diameter of 3,5 meters and a height of 0,3, 0,7 or 1,4 meters.

Once the fish have matured enough they are transferred to 'culture' tanks with a diameter of 7 meters and a height of 1,2 or 1,8 meters. Once the tilapia fish have fully matured, the fish are removed from the tanks and can be inspected on the nearby working surfaces. To make it easier to inspect or remove fish, the tanks will be outfitted with net enclosures called Hapas, see Figure 25 (right).

Figure 25: (left) Fish farming tanks. (right) Hapas in a fish pond

Based on the required number of tanks, and the necessary support equipment, the following floor design was made for the fish farm. The floor layout can be seen in Figure 26. Similar to every other floor, the fish farm has staircases and elevators at the sides. The center of the floor is a small room in which trolleys are stored. These trolleys are used to transport fish from one tank to another, or to move fish to the working surfaces or up to the Food Processing Floor.

The sixteen water tanks, divided over three rooms, contain the Tilapia fish of various sizes and life cycle phases. These tanks are connected by pipes to water treatment units, which filter the water in the tanks to remove waste, excess feed and other undesired substances. Finally, four buffer tanks, containing water, are present on each Fish farming Floor to cope with water losses in the system.

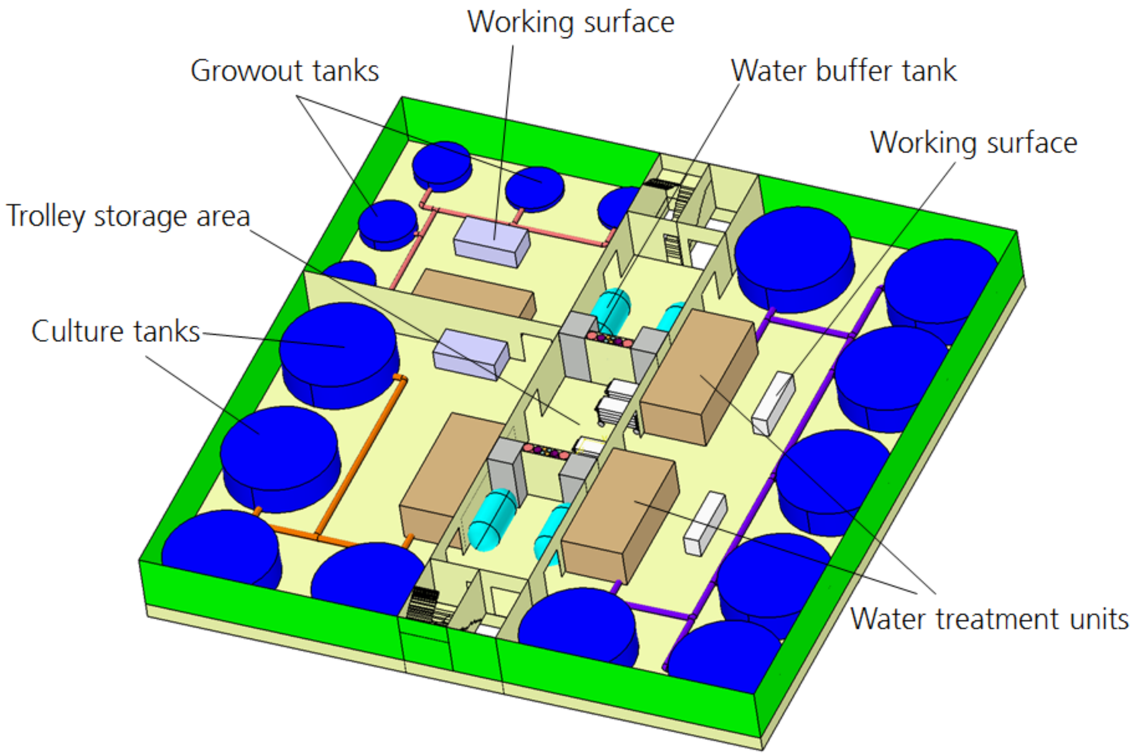


Figure 26: Fish Farming Floor design

Based on the maturity of the fish, Tilapia will have different feeding requirements [10], as illustrated in Table 9 below. Different stocking rates are possible for Tilapia fish of various sizes as indicated in the first column. The second and third columns indicate the (average) initial and final weight of the fish for each growth stage. The fourth column indicates the growth period in days per growth stage, while the fifth column presents the average feeding rate per day in percentage of fish body weight during the growth stages. Based on the average fish weight per growth stage and this feeding rate, it is possible to determine the average daily feed requirements per fish per day. This is listed in column six. Finally, the total feed requirements per fish per growth period are found by multiplying the required feed per day by the number of days per growth stage. At the bottom of the table, the total feed required for one fish during its entire growth cycle is listed

Table 9: Tilapia fish feeding requirements [10]

Stocking Rate [fish/m³]	Weight [grams]		Growth Period [days]	Daily Feeding Rate [%]	Daily feed requirement [g/fish*day]	Total feed requirement [g/fish*growth period]
	Initial	Final				
8000	0,02	1	30	17	0,0867	2,6
3200	1	5	30	12	0,36	10,8
1600	5	20	30	8	1	30,0
1000	20	50	30	6	2,1	63,0
500	50	100	30	4	2,625	78,8
200	100	250	50	2	3,5	175,0
100	250	450	70	1	4,2	294,0
Total feed requirement [grams/fish]						**654,2**

For the design of the fish farm, it was assumed that the fish in each of the stages listed in Table 9 would be in separate tanks from the fish in other growth stages. To ensure a steady state production, each growth stage should have the same daily output of 'mature' fish. Eventually, five tank sizes were used, rather than seven, due to limitations on the available space (especially the available height).

By altering the size of the tanks, as well as the number of tanks per growth stage, it was possible to alter the daily output of fish. Table 10 shows the sizes and maximum capacities of the fish tanks on the Fish Farming Floor. The maximum output of the entire system will be equal to the minimum daily output of one tank type. The daily output of a fish tank was calculated by dividing the maximum number of fish per floor (see Table 10) by the corresponding number of days of that growth period (see Table 9).

It should be noted that the actual number of fish per tank may be lower than the maximum capacity. The smaller tanks will not be at maximum capacity, because the larger tanks will not be able to hold all of the smaller fish as they grow.

Table 10: Fish tank diameters and stocking rate

Tank	Diameter [m]	Height [m]	Stocking rate [fish/m³]	Max. Fish per tank [-]	Tanks per floor [-]	Max. Fish per floor [-]
Growout tank	3,5	0,3	8.000	23.090	1	23.090
Growout tank	3,5	0,7	3.200	21.551	1	21.551
Growout tank	3,5	1,4	1.600	21.551	1	21.551
Culture tank	3,5	1,2	1.000	11.545	2	23.090
Culture tank	7,0	1,8	500	34.636	1	34.636
Culture tank	7,0	1,8	200	13.854	3	41.562
Culture tank	7,0	1,8	100	6.927	7	48.489

It was found that even though the largest culture tanks, with a stocking rate of 100 fish/m³, had had the largest maximum capacity, see Table 10, the daily output was the lowest, due to the long growth period of 70 days. The daily output of fish per floor for these tanks, and hence for an entire Fish Farming Floor, was calculated to be 693 fish per day.

In Table 9 it can be seen that a mature fish has an average weight of 450 grams, so an output of 693 fish per day corresponds to 312 kilograms of fish output per day per floor. According to [11], only 30 – 35% of the Tilapia fish can be used as filet, while the rest is discarded. Taking the lower value of 30%, this would mean that about 94 kilograms of Tilapia filet can be produced per Fish Farming Floor (FFF).

During its complete life cycle, a tilapia fish requires 654 grams of feed, as seen in Table 9. Thus per day, each floor will require 693 times this amount, for a total of 453 kilograms per floor, in fish feed in order to allow the tilapia to grow optimally. Only part of this fish feed results in weight increase of the fish, the remainder becomes waste which needs to be removed from the water. With a total feed requirement of 453 kilograms per floor and a fish output of 312 kilograms, the difference of 142 kilograms will be (roughly) the waste output per day per floor.

The Tilapia fish will be fed a mixture of (processed) inedible plant biomass from the Plant Cultivation Floors and fishmeal bought from an external supplier. Fishmeal, made from non-edible parts of fish, is an excellent feed source for fish due to its amino acid balance, protein content and vitamin content, among other things [12]. There is some uncertainty about the regulations regarding the use of fishmeal made from Tilapia for the purpose of Tilapia farming

[13] [14], but here it will be assumed that this is prohibited. As such, any fishmeal which is used for feeding the Tilapia will need to be bought from external suppliers of (non-tilapia) fishmeal.

From [12] it can be found that using a mixture of plant protein sources can be a suitable substitution of fishmeal in fish feed, inducing no significant changes in feed intake and only impacting growth performance when plant protein sources are exclusively used as fish feed. It is therefore assumed that the required daily fish feed can be met by supplementing 1 ton of inedible biomass from crops grown on the Plant Cultivation Floors with high-protein fishmeal bought from an external supplier. Subtracting 1 ton from the daily feed requirements yields that 360 kg/day of fish feed will need to be bought. An overview of important input and output values for the Fish Farming Floors is presented in Table 11.

Table 11: Summary of fish farm production

Parameter	Amount per day	Amount per year	Unit
Number of fish floors per VF	3	3	-
Total output of mature fish per floor	693	252.945	Fish
Total output of mature fish per VF (3 x FFF)	2.079	758.835	Fish
Total mass of mature fish per VF (3 x FFF)	935,5	341.457,5	kg
Edible fish output per VF (fish filet) (3 x FFF)	280,7	102.442,7	kg
Feed requirements per VF	1.360,1	496.436,5	kg
(Processed) Inedible plant biomass fish feed	1.000	365.000,0	kg
High-protein fish feed	360,1	131.436,5	kg
Total waste output per VF	1.079,3	393.968,3	kg
Non-edible fish output per VF (fishmeal)	654,8	239.014,8	kg
Waste output per VF (e.g. faeces)	424,5	154.953,5	kg

The 1.079 kilograms of waste and non-edible tilapia fish produced by the fish farms each day are delivered to the Waste Management Floors, where it will be processed to generate biogas or extract nutrients. The waste management process is described in Chapter 11.

6.4 Equipment List

To function as intended, the Fish Farming Floors will require some equipment. A list of the expected required equipment can be found in Table 12, along with best estimates on the equipment cost. Scaling effects on the cost due to bulk purchases have not been considered.

Table 12: Initial cost estimation for the equipment of three Fish Farming Floors [FY12]

Equipment	Units [-]	Price [€/unit]	Total [k€]
Growout Tanks	15	6.000	90
Culture Tanks	33	10.000	330
Liqui-Cell Membrane contractors	6	1.500	9
Nitrification and denitrification system	6	15.000	90
Oxygenation system	6	1.000	6
Sludge removal system	60	7.000	420
Solid waste removal system	6	5.000	30
UV Lighting (Bacteria Annihilation)	6	4.000	24
Alkalinity sensors	60	1.000	60
Ammonia sensors	60	150	9
Carbon dioxide sensors	60	100	6
Nitrogen Oxide sensors	60	100	6
Oxygen sensors	60	100	6
pH sensors	60	150	9
Thermonitor	60	50	3
Water flow sensors	60	70	4,2

Equipment	Units [-]	Price [€/unit]	Total [k€]
Water level sensors	60	40	2,4
Feeding system	60	1.000	60
Hapas	800	30	24
Heating System	60	1.000	60
Low Level Lighting	60	100	6
Pumps	60	800	48
Sorting Tables	12	300	3,6
Hapas moving cranes	3	1.500	4,5
Total set-up costs			**1.310,7**
Margin of 20%			**262,14**
Total set-up costs with 20% margin			**1.572,84**

7 Nutrient Delivery System

The Nutrient Delivery System (NDS) for the Vertical Farm incorporates each aspect of the building related to the storage, delivery and retrieval of water and nutrient solutions to the various plants.

7.1 Assumptions

Certain assumptions were made during the design study and the relevant ones for the Nutrient Delivery Floor are listed below:

- It is assumed that no water loss occurs in the fish farming, waste management and food processing facilities.
- It is assumed that water usage for housekeeping operations, fire sprinklers, and other standard building systems is negligible.
- It is assumed that excess nutrient solution is recovered from the Grow Pallets / Grow Units and it is assumed that all the transpirated water is recovered and recycled for use in the Fluid Delivery System. In short, it is assumed that the only water loss in the Vertical Farm is the water which is contained within the fruits, vegetables and inedible plant biomass produced on the Plant Cultivation Floors.
- It is assumed that the edible and inedible biomass output (fresh basis) of the Plant Cultivation Floors is 100% water (for calculation purposes). This gives a margin on the amount of water leaving the Vertical Farm.
- The Waste Management Floors and Fish Farming Floors will produce fertilizer for plant cultivation. For this study, these nutrient sources are not taken into account. Instead, commercial, highly concentrated, fertilizer (Beyond ™) is used to provide the plants with the needed nutrients. Later studies shall investigate the total fertilizer production on the Waste Management and Fish Farming Floors and determine the optimal usage of the produced fertilizer as nutrient supplements.
- No estimate has been calculated for the amount of acid which is consumed per day.

7.2 System Description

It was decided that the numerous benefits of aeroponics, such as reduced water and fertilizer usage and increased crop production, outweighed the drawbacks of increased complexity and cost. As seen in Figure 27, aeroponics consists of growing plants in air and spraying the roots with precisely controlled amounts of nutrients and water.

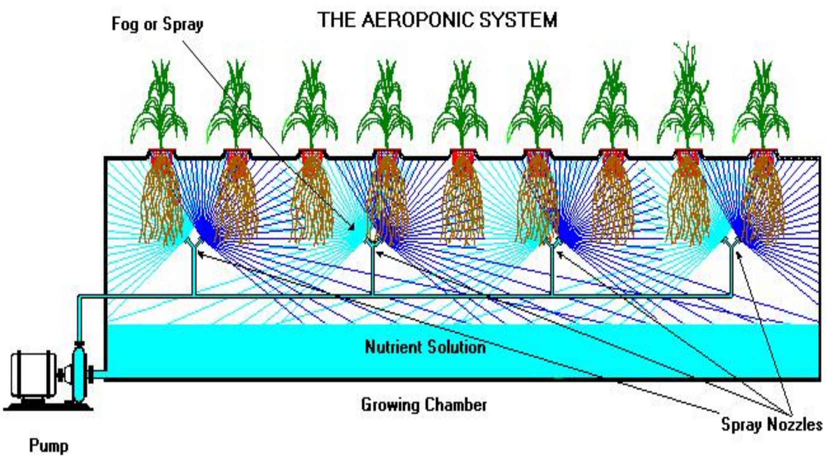


Figure 27: Standard aeroponic system. [15]

According to AgriHouse, Inc., growers choosing to employ the aeroponics method can reduce water usage by 98%, fertilizer usage by 60%, and pesticide usage by 100%, all while maximizing their crop yields by 45 – 75% with respect to other cultivation methods [9]. Moreover, the NASA Small Business Innovation Research (SBIR) results demonstrated that this aeroponic technology delivers an 80-percent increase in dry weight biomass per square meter, when compared to hydroponic and soil-based growing techniques [9].

Following delivery of the nutrient solution into the root zone of the plants, the aerosolized mist will be absorbed through the roots. The majority of the nutrients, and part of the water, will be used by the plants to grow. Excess nutrient solution will be pumped back to the NDS rooms on the Plant Cultivation Floors, while part of the absorbed water will be transpirated into the air.

The air management system will cause the humid air to be removed to the Environmental Control Floors where the air will be dehumidified. During this process, most of the water in the air will be recovered and stored in a buffer tank. From there it will be returned to the main tanks on the Nutrient Delivery Floor.

Figure 28 provides a diagram of the components of a closed-loop aeroponic system. This can be used to design the NDS and to generate a list of equipment needed for the system.

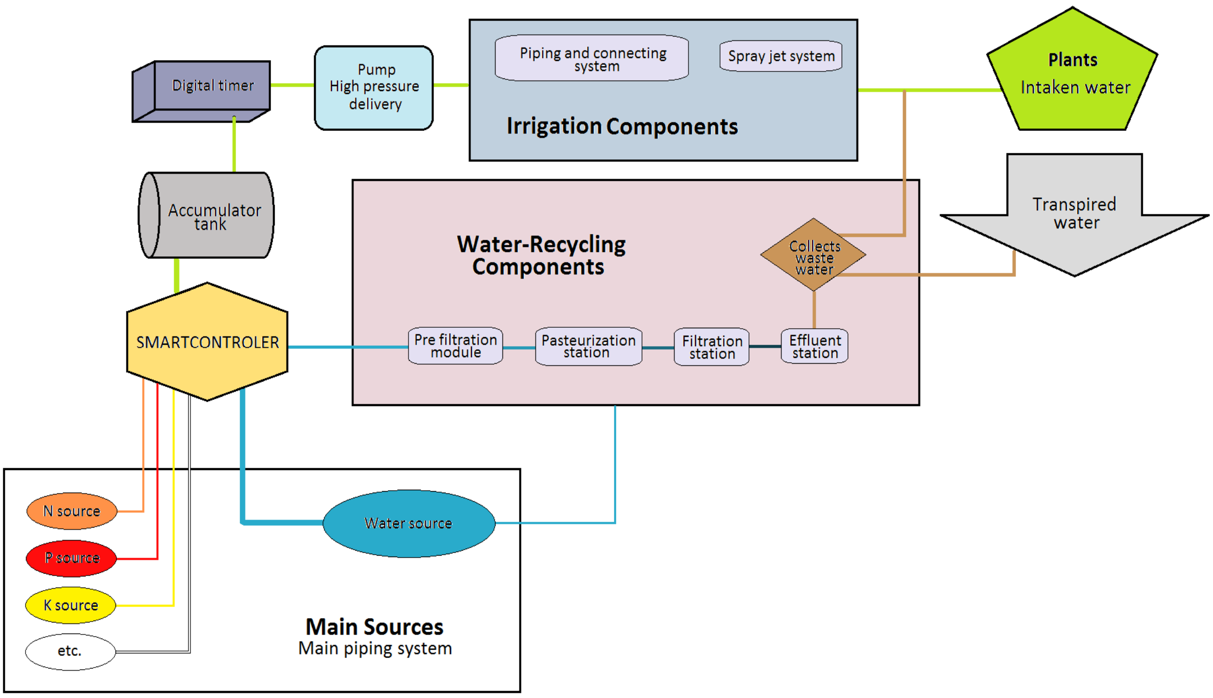


Figure 28: Schematic of the components of a closed-loop aeroponic system

The Nutrient Delivery System was designed such that the main water and nutrient tanks would occupy a floor at the top of the Vertical farm. Since each of the Plant Cultivation Floors was assigned to one specific crop, it was decided that mixing of the nutrients with water and acid to obtain the required solution would be done on the plant floor itself and the water and nutrients would be piped down to small storage tanks on the plant floors, see Figure 29.

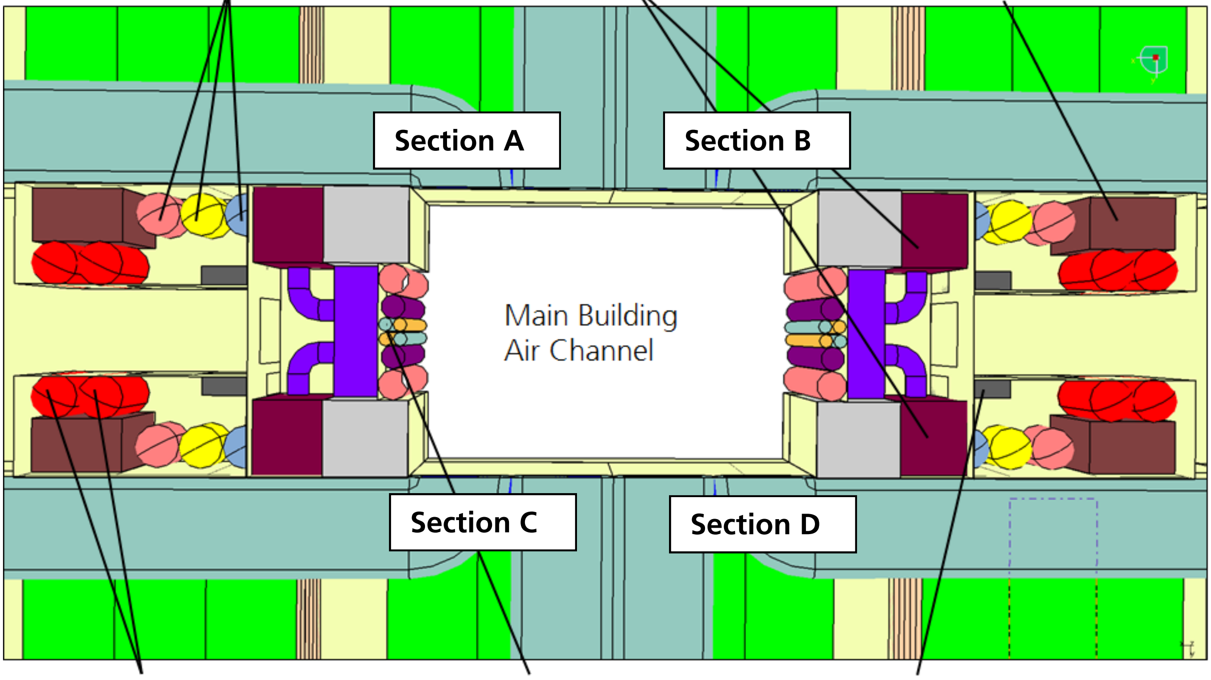


Figure 29: Close up view of the nutrient delivery system on the Plant Cultivation Floors

A mixing tank, combined with a mix computer which measures pH- and EC-values as well as the temperature of the nutrient solution, is used to obtain the proper nutrient mix for the plants being grown in the corresponding floor section. Each floor grows only one crop type, but the difference in plant maturity between the sections means that the plants will require (slightly) different nutrient solutions. Therefore, each Plant Cultivation Floor has four NDS rooms (one per section).

The mix computer ensures that the correct quantities of the various nutrients are mixed with the desired amount of water. The mix computer also measures the pH, electrical conductivity (EC) and temperature of the nutrient solution and adjusts the nutrient solution according to the measurement data. Figure 30 shows an example of a mix computer with associated piping, valves, sensors and large mixing tank.

Once the desired nutrient solution has been created it is pumped towards the Grow Units at high pressures of several hundreds of psi. This high pressure is necessary to allow for pressure losses in the piping, while still maintaining a sufficiently high pressure to aerosolize the nutrient solution when it is forced through the aeroponic misters into the root zones of the Grow Pallets.

Figure 30: FD-326P solution mixer system [source: FITO-AGRO Ltd.]

Since the actual mixing and the final distribution of the nutrient solution occurs on the Plant Cultivation Floors, the Nutrient Delivery Floor, see Figure 31, only contains tanks to hold the nutrients, water and acid required for the Vertical Farm operations, and pumps to distribute this through the building. The pumps will be connected to the main pipelines running through the center of the building.

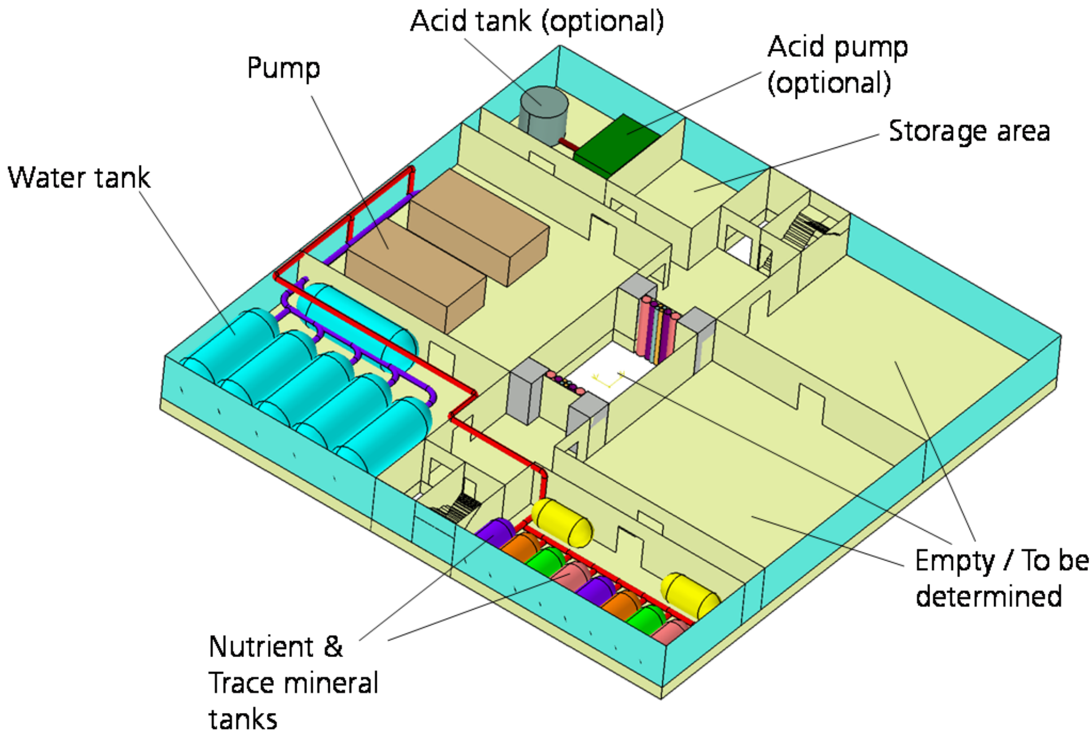


Figure 31: Nutrient Delivery Floor layout

There are empty rooms which can be used for storage of equipment, or some other to be determined purpose like for example the fertilizer facility (incl. fermentation tubes), which is currently located on the Waste Mgmt. Floor. The acid tank (incl. pump) will most likely be in cooperated on each Plant Cultivation Floor and is only for the sake of completeness displayed in Figure 31.

7.3 Water and Nutrient Consumption

The Vertical Farm contains 25 Plant Cultivation Floors with a total grow area of 92.718 m^2. Combining the total grow area per crop with information from [6], it is possible to determine the water consumption per crop species per day. This can be found in Table 13 below. The second column shows the total grow area for each crop. The third and fourth columns contain data on the amount of water transpirated by the plants each day. To prevent dehydration, it is necessary for the NDS to provide at least the same amount of water to the plants as is transpirated.

The fifth column of Table 13 shows the amount of water which is not transpirated by the plants, but is instead stored in the edible and inedible biomass. To have a margin on the amount of water usage, it is assumed that the water content of the total (inedible and edible) biomass production is 100%. The biomass output of the Vertical Farm was previously calculated in Chapter 5.4. Finally, in the sixth column the sum of the transpirated water uptake and the 'non-transpirated' water uptake is presented. The calculated water uptake values are rounded to the nearest kilogram.

Table 13: Total water consumption per day

Crop	Total grow area [m²]	Transpirated water uptake [kg/m²*day]*	Total transpirated water uptake [kg/day]	Crop water uptake [kg/day]	Total water consumption [kg/day]
Lettuce	22.032	1,77	38.997	4.277	43.274
Cabbage	9.180	1,77	16.249	1.061	17.310
Spinach	5.508	1,77	9.749	619	10.368
Carrots	7.344	1,77	12.999	1.385	14.384
Radish	4.590	1,77	8.124	942	9.066
Tomatoes	11.016	2,77	30.514	4.645	35.159
Peppers	7.344	2,77	20.343	2.842	23.185
Potatoes	9.180	2,88	26.438	2.513	28.951
Peas	11.016	2,46	27.099	2.671	29.770
Strawberries	5.508	2,22	12.228	1.715	13.943
Total			**202.740**	**22.670**	**225.410**

* Taken from [6]

Aside from the water needed to grow the crops, it is also necessary to consider the required nutrients. The best-case situation would be to have crop-specific nutrient solutions, which will provide the optimal growth for that crop. Nutrient solutions are usually used for a variety of crops and any nutrients which are not absorbed by the plants are either recycled or discarded. Thus, for initial calculations it will be assumed that the nutrient mixtures will be the same for all crop species.

For the current study, it was calculated how much nutrient solution would be required if a commercial product would be used. The corresponding cost is calculated in Chapter 12.3.3. The selected commercial nutrient solution is Beyond ™, which has also been used by NASA for plant cultivation [9]. From [16] it can be found that the recommended dose of the highly concentrated nutrient solution is 5 mL per 10 gallons of water, or roughly 0,132 ml/L. Multiplying this recommended dose with the total water consumption, it is found that the total usage of Beyond ™ will be about 29,75 Liters per day.

It should be noted that the Waste Management System, which will be discussed in a later chapter, contains a fertilizer facility which is capable of extracting nutrients from waste. Currently, all the waste is used for biogas production, as discussed in Chapter 11, and the amount of nutrients which might be recovered using the fertilizer facility has been left for future studies, but with the Vertical Farm producing several tons of waste each day, it is expected that a significant part of the required nutrients can be recovered.

Furthermore, nitrate from the waste water of the fish farms can be used as nutrient supplement for plant cultivation.

7.4 Equipment List

Based on an analysis of the components of an aeroponic system, and the items identified from Figure 31, it is possible to create a list of required equipment. Table 14 shows this equipment list for the nutrient delivery system and the best estimate for the equipment cost.

Table 14: Equipment list and cost estimation for the Nutrient Delivery Floor [FY12]

Equipment	Units [-]	Price [€/unit]	Total [k€]
Water tanks	6	10.000	60
Nutrient tanks	10	5.000	50
Acid tank	1	5.000	5
Pumps	2	10.000	20

Equipment	Units [-]	Price [€/unit]	Total [k€]
Acid pump	1	5.000	5
Pipes	-	-	1.750
Water tanks (Plant Cultivation Floors)	100	1.000	100
Nutrient tanks (Plant Cultivation Floors)	100	500	50
Mix Computers	100	5.000	500
Pumps (Plant Cultivation Floors)	100	1.000	100
Smart controllers	200	2.400	480
Accumulator tanks	200	250	50
Pumps- high pressure delivery (PCF)	200	250	50
Digital timers	200	400	80
Water recovery systems (PCF)	200	800	160
Spray jets	418.064	8	3.345
Connectors	418.064	4	1.673
Total set-up costs			**8.478**
Margin of 20%			**1.695,6**
Total set-up costs with 20% margin			**10.173,6**

8 Lighting and Power

The energy consumption of the Vertical Farm is expected to be one of the main factors determining the economic feasibility. Artificial lighting is chosen for the current design with the following factors influencing the choice:

- Vertical farms are typically designed for megacities, but can also be considered for Taiga- and desert regions. Typically, these are places where the availability of sunlight is an aberration. For example, Taiga regions have long winters where the sunlight is unavailable, while the desert sun light is too extreme to use directly for plant cultivation.
- 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 photoperiod required by the plants, specific ranges of spectrum, luminous efficacy etc. Thus, plant growth can be optimized for a faster and a greater yield with artificial lighting.

8.1 Assumptions

Certain assumptions were made during the design study and the relevant ones for the Lighting System are listed below:

- Shuttering of the LED panels was not considered. Future studies will investigate the potential power (and energy) savings which can be achieved by shuttering.
- The heat transfer from the LED panels to the surrounding air is negligible. All heat is transferred to the cooling fluid of the LED cooling system. In cold climates or during winters, the cooling fluids can be used to transfer heat from the LEDs to other systems if necessary.
- It is assumed that the heat exchangers for the LED cooling system have a coefficient of performance (COP) of 4. This is close to the maximum value achieved in state-of-the art heat exchangers [18] [19].
- 70% of the LED power consumption is transformed into heat [20]
- The cooling system for the LEDs is designed to handle a worst case scenario of 25 Plant Cultivation Floors, each with a grow area of 5.508 m^2 (such as for example strawberries), but with a crop PPF demand of 324 $\mu mol/m^2*s$ (such as demanded by potatoes [6]). This way, quite a conservative calculation was done, which reflects a big margin.
- The Photosynthetic Photon Flux at canopy level does not change with varying distance between LED panel and plant canopy
- The power consumption of the LED panel is 230 Watt, meaning 230 Watt-hours per hour [17].
- The power consumption scales linearly with the amount of PPF emitted by the panel.
- The light spectrum can be tailored independently from the intensity, meaning that reducing the emitted PPF does not affect the light spectrum.
- The power and energy consumption of the lighting system for the Germination Floor are assumed to be 2% of the combined Plant Cultivation Floor power and energy consumption. This is close to the ratio of LED panels on the Germination Floor to LED panels on the combined Plant Cultivation Floors.
- Only one type of LED-panel was taken into account for this study as a first estimate. Later studies will investigate the optimal LED-panel design for each crop along with the expected power consumption of those panels.
- No explicit margins are added onto the peak power demands presented in this chapter. The energy consumption was calculated by multiplying the peak power demand with the

operating time. The power and energy demands may contain some (additional) margin due to the assumptions used during the calculations.

- Not considered in the power calculation are the plant life cycle depending variable light intensity adjustments. Early plants (e.g. sprouts need less light intensity than plants that are in the vegetative state). This way the power calculation inhabits a solid margin, which need to further investigated in the future.

8.2 LED technology for lighting

LED (Light Emitting Diode) technology is chosen for the current Vertical Farm design with its various advantages over other artificial lighting technologies. LEDs emit a relatively low level of thermal radiation, have no hot electrodes, and have no high-voltage ballasts. LEDs 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 LEDs is that it is possible to modify the irradiance output to approximate the peak absorption zone of chlorophyll.

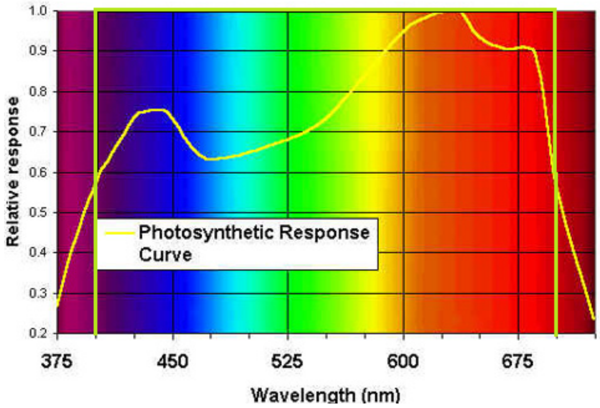
8.3 Baseline Design

The baseline design of the lighting system consists of several LED panels of the type Bloom Power black240 [17]. One panel, designed during the CE-study is shown in Figure 32 and has the following properties, see Table 15:

Table 15: LED panel parameters [17]

Parameter	Value
Panel name [-]	Bloom Power black240
Number of LEDs [-]	180 (Class 3W3)
Power consumption [Watt-hours]	230
Color-range [-]	6-band multispectral
Photosynthetic Photon Flux (PPF) [µmole/m²*s]	900
Recommended Image area [m²]	1

Based on the recommended image area, one panel is required per square meter of growth area. The proposed Vertical Farm design has a growth area of approximately 93.000 m², requiring 93.000 LED panels. Including an additional 2.000 panels for the germination units and using a safety margin of about 5%, 100.000 LED panels are required for the Vertical Farm. The safety margin is applied to account for failures of panels, as well as to cope with possible increased demand. If the assumption on the amount of Grow Lids which can be stacked in a Germination Unit is too low for example, more LED panels would be required.



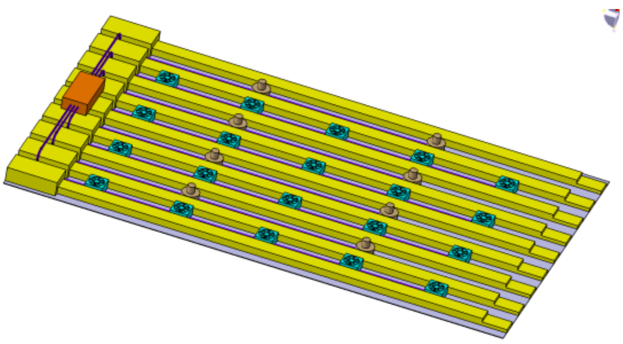


Figure 32: (Left) Quantum response – Relative photosynthetic response versus wavelength. The quantum response assumed for the PAR parameter (green line) is compared to the average plant response (yellow line); high performance LED panel, designed during the CE-study. (Right)

The LEDs on the panel provide different wavelengths leading to a spectrum suitable for plant growth. Figure 32 (left) shows the spectrum of the panel compared to the relative photosynthetic response.

The selected plant species have different illumination requirements in terms of PPF (Photosynthetic Photon Flux). Therefore, the panels are not operated on maximum power. The panels will be operated on 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 twelve respectively sixteen hour periods depending on the plant species [6].

For the power demands of the LED panels, it is assumed that the power consumption scales linearly with the amount of PPF emitted. Thus, if the PPF output is halved, the power demand will be halved as well. Then, based on the calculated power demands and the desired daily lighting periods, the energy demand can be calculated. Table 16 shows the power and energy demands with respect to the plant species.

Table 16: Power and energy demand of the Plant Cultivation Floor lighting system

Crop	Total Growth Area [m²]	PPF demand [µmol/m²*s] [6]	Daily Lighting period [h] [6]	Peak power demand [kW]	Daily Energy Demand [kWh]
Lettuce	22.032	196,8	16	1.108,1	17.729,6
Cabbage	9.180	196,8	16	461,7	7.387,2
Spinach	5.508	196,8	16	277	4.432
Carrots	7.344	196,8	16	369,4	5.910,4
Radish	4.590	196,8	16	230,9	3.694,4
Tomatoes	11.016	312,5	12	879,8	10.557,6
Peppers	7.344	312,5	12	586,5	7.038
Potatoes	9.180	324,1	12	760,4	9.124,8
Peas	11.016	277,8	12	782,1	9.385,2
Strawberries	5.508	254,6	12	358,4	4.300,8
Total				**5.814,3**	**79.533**

For the Germination Floor, the power demand and energy consumption were assumed to be 2% of the total power and energy demands of the combined Plant Cultivation Floors, which is roughly the ratio between the number of panels on the Germination Floor and the combined number of panels on the Plant Cultivation Floors. This assumption gives, respectively, a power consumption of 116 kW and 1.591 kWh of daily energy usage for the Germination Floor.

Table 17: Power and energy consumption of the Plant Cultivation and Germination Floors

Floor	Peak Power demand [kW]	Daily Energy Consumption [kWh]
Plant Cultivation Floors	5.814,3	79.533
Germination Floor	116,3	1.590,7
Total	**5.930,6**	**81.123,7**

Table 17 summarizes the power and energy consumption of the LED panels on the Germination Floor and the Plant Cultivation Floors.

8.4 LED cooling

To prevent the LED panels from breaking down or transferring excess heat to the air, it is necessary to cool them. The assumption was made that the transfer of heat from the LEDs to the air is negligible, even though 70% of the power used by the lighting system is transformed into heat [20]. Instead this excess heat will be transferred to the liquid coolant which will be used to maintain the desired panel temperature.

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 5.931 kW. The total amount of heat produced is 70% of this value, so about 4,2 MJ/s.

For the design of the LED cooling system, a worst case scenario is defined where a Plant Cultivation Floor has a maximum grow area and a maximum PPF demand. The maximum grow area for a single Plant Cultivation Floor is 5.508 m², such as for strawberries. From Table 16 it can be found that the maximum required PPF for the VF crops is 324 µmol/m²*s (for potatoes). Taking this PPF demand, with the maximum plant cultivation area per floor, a maximum power demand per floor of 456 kW can be found. 70% of this power consumption is transformed into heat, resulting in a total of 319 kW of heat per Plant Cultivation Floor which needs to be transported out of the building in the worst case scenario.

Per Plant Cultivation Floor there are two heat exchangers, which will be sized to handle 200 kW of cooling. Two heat exchangers per Plant Cultivation Floor results in 50 heat exchangers in total, for all the Plant Cultivation Floors in the VF. Table 33 shows a close-up of a heat exchanger system on a Plant Cultivation Floor.

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. 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. The COP is a unitless parameter, while EER and SEER are given in Btu/W*hr. As such, for ease of calculations, the COP is used for the calculations described in this report.

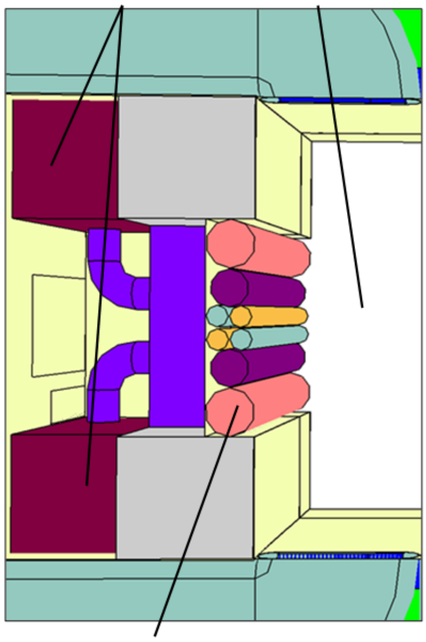


Figure 33: Close-up view of the LED cooling system on the Plant Cultivation Floors

From [21] it can be found that new residential air conditioning systems in USA require a SEER rating of at least 13, 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 [18, 19].

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 four 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. This is also indicated in Table 21 in the next chapter.

8.5 Power and Energy consumption

In Table 18, the peak power demand and the energy consumption for other subsystems is listed. The values for the lighting system were calculated previously, while the values for the environmental control system are calculated in Chapter 9.3.3. The power demand and daily energy consumption for all the other values are estimated on best engineering estimates.

Table 18: Peak power demand and energy consumption for the VF

Subsystem	Peak power demand [kW]	Daily operation time [h]	Daily energy consumption [kWh]*
Fish Farming	15	24	360
Waste Management	15	24	360
Food Processing, Staff and Control	38	-	252
Germination	150	24	3.600
Environmental Control	15.123	-	327.203
Nutrient Delivery	15	24	360
Lighting	5.931	-	81.124
Total Needed	**21.287**	**-**	**413.259**

* Based on constant peak power consumption during the operating times of the subsystems

8.6 Equipment List

The equipment required for the lighting system to work properly is listed in Table 19, along with cost estimation based on best engineering estimates. The structure required for the lighting panels is already considered in the cost of the Grow Units.

Table 19: Initial cost estimation for the lighting systems [FY12]

Equipment	Units [-]	Price [€/unit]	Total [k€]
LED panels (Germination Floor)	2.000	699	1.398
LED panels (Plant Cultivation Floors)	93.000	699	65.007
LED panels (spare/ margin)	5.000	699	3.495
Heat Exchanger systems (including piping)	50	20.000	1.000
Total set-up costs			**70.900**
Margin of 20%			**14.180**
Total set-up costs with 20% margin			**85.080**

9 Environmental Control

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 floors. As part of the air management (closed-loop approach), it is necessary to filter out contaminants and trace gases, such as ethylene and other volatiles, which are released into the air as by-products of the plant cultivation. It already has to be stated the H_2O recovery and trace gas separation are two expensive technologies, which might not be feasible for the Vertical Farming.

9.1 Assumptions

Certain assumptions were made during the design study and the relevant ones for the Environmental Control Floors are listed below:

- Only rough estimations and preliminary calculations are done for the HVAC system during this study.
- For the purposes of this design study, only the effects of the Plant Cultivation Floors on the air quality of the Vertical Farm were taken into account. The influence of the Fish Farming Floors, Waste Management Floors, Supermarket and Delivery Area, Food Processing Floor, Germination Floor and the Nutrient Delivery Floor are assumed to be minor compared to the Plant Cultivation Floors. Nevertheless, these systems are, from an economical point of view, covered within the cost calculation in chapter 12.2.
- The heat from the LED panels is transferred to cooling liquid rather than the air.
- It is assumed that 100% of the transpirated water can be recovered
- It is assumed that the heat exchangers will have a coefficient of performance of 4, as was mentioned in the previous chapter.
- The desired dry bulb temperature of the air is assumed to be 25 degrees Celsius, and it is assumed that the relative humidity should be 70%.
- The transpiration rate of plants remains constant with changing temperature and changing relative humidity (RH), until air reaches 100% RH.
- Fan efficiency is assumed to be the ratio of power output from the impeller to electrical power input. This efficiency varies depending on the exact operating conditions, but with the right fan selection a total peak efficiency of over 80% is possible [22].
- Furthermore, the Air Movement and Control Association (AMCA) requires that fans be selected such that they operate within ten points of the total peak efficiency [22]. Meaning that the fans should be selected such that, over the entire operating range, the efficiency is within 10% points of the maximum. As such, an average fan efficiency of 80% is taken for the calculations in this chapter.
- 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.
- For the two exhaust/inlet 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 280 m^3/second, so 140 m^3/second. For the expected power consumption of one of these fans, the combined power consumption of three of the fans in the center of the environmental floor is taken, and this is multiplied by a factor of 1,4 to obtain a power consumption of 227 kW, not yet taking into account any losses.

9.2 Baseline Design

In total, there are three Environmental Control Floors, controlling the air quality of eight or nine Plant Cultivation Floors each. The design for the Environmental Control Floor, shown in Figure 34, 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 Plant Cultivation Floors into the Environmental Control Floor through the air channels and duct 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 Nutrient 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 center of the floor, where it enters the large air channel which leads back down to the Plant Cultivation Floors. 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.

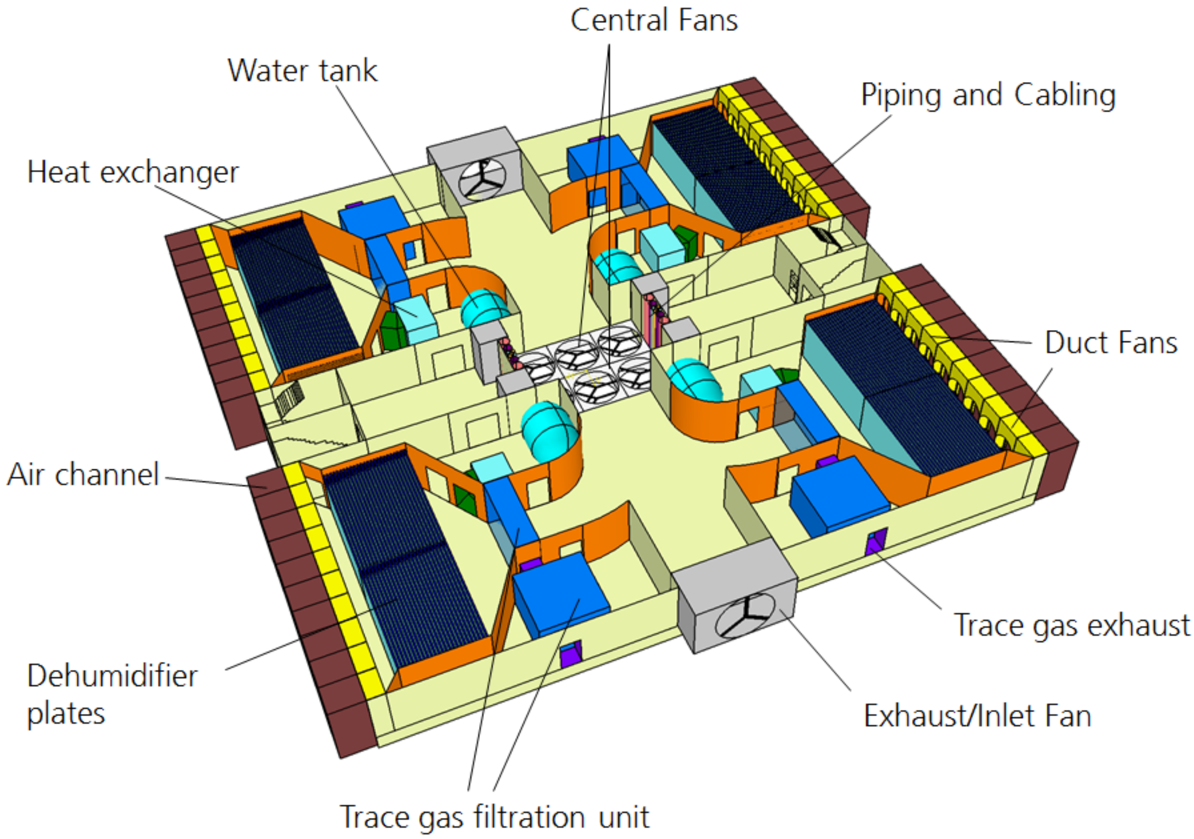


Figure 34: Environmental Control Floor design

The heat load 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 35. The roof also holds the pumps and cooling fluid tanks which are required for the various heat exchangers in the building to work, including those for the LED cooling. The cooling fluid which is pumped through the building to the heat exchangers flows through the piping which can be seen in Figure 34.

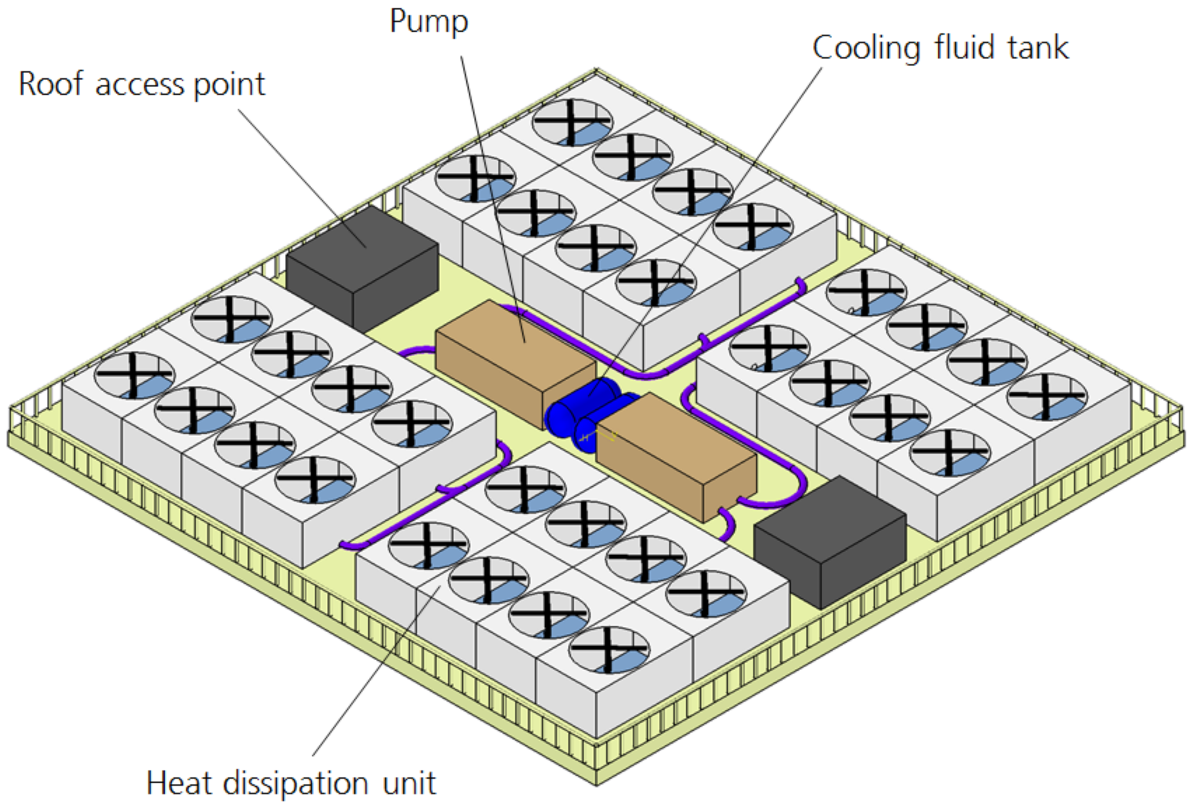


Figure 35: Roof design

Carbon dioxide levels desired for optimal plant growth, and increased yield, 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 Floors. Using data from [6] and the calculated grow area for the crops it was possible to calculate the amount of CO_2 absorbed by the plants each day. The results can be found in Table 20.

Table 20: Carbon dioxide uptake per day [6]

Crop	Grow area [m²]	CO_2 Uptake [g/m²*day]	Total CO_2 uptake [g/day]
Lettuce	22.032	10,70	235.742
Cabbage	9.180	9,88	90.698
Spinach	5.508	10,70	58.936
Carrots	7.344	22,50	165.240
Radish	4.590	16,31	74.863
Tomatoes	11.016	36,24	399.220
Peppers	7.344	33,98	249.549
Potatoes	9.180	45,23	415.211
Peas	11.016	45,26	498.585
Strawberries	5.508	34,82	191.789
Total			**2.379.833**

At sea level conditions, 2.380 kilograms of carbon dioxide gas corresponds to about 1.270 m³. In Chapter 11, which discusses the Waste Management Floors, it is calculated that the total amount of CO_2 which is produced by the Vertical Farm is 983 m³/day. Thus, the Vertical Farm will require 287 m³/day of CO_2 from external sources.

9.3 Heating, Ventilation and Air-Conditioning (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 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.

As mentioned previously, it is assumed that the temperature of the air in the Vertical Farm should be kept at 25 degrees Celsius, 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 temperature relative humidity, until the air reaches a RH of 100%.

It is assumed that the heat transfer from the LEDs to the air is negligible and 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.

9.3.1 Flow Rate

Psychrometrics is a discipline dealing with the determination of physical and thermodynamic properties of gas-vapor mixtures. For a specific constant pressure, the thermodynamic properties of a gas-vapor mixture can be determined and presented graphically in a psychrometric chart [23]. Figure 36 shows such a psychrometric chart for air at sea level elevation [24]. 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 degrees Celsius, with a RH of 70%, as mentioned earlier. According to Figure 36, at 25 degrees Celsius and 70% RH, the humidity ratio is 13,8 grams of water per kilogram of dry air. At the same temperature, but at 100% RH, the humidity ratio is about 20 grams of water per kilogram of dry air.

Thus, the maximum water uptake capacity of the air is 0,0062 g/g of dry air, when the temperature is kept constant. At 25 degrees Celsius, the density of air at sea level pressure is 1,1839 kg/m^3, which means that one gram of dry air occupies 8,45*10^{-4} m^3 and hence, the maximum amount of water which can be absorbed by the air is 7,34018 g/m^3.

Furthermore, it can be determined that the maximum amount of water transpirated from the plants into the air is 2,88 kg/m^2*day [6] in the worst case, which corresponds to 0,0333 g/m^2*s. A maximum grow area of 5.508 m^2 per floor was calculated. The total amount of air volume per floor is roughly 5.600 m^3 (floor is 40 m by 40 m by 3,5 m). This means that 1 m^2 of grow area corresponds to 1,017 m^3 of air and thus the maximum transpiration rate is 0,0328 g/m^3*s.

With this transpiration rate it would take about 224 seconds for the air to become saturated with water. This means the air over the plant canopy needs to be refreshed once every 224 seconds, or (roughly) once per four minutes.

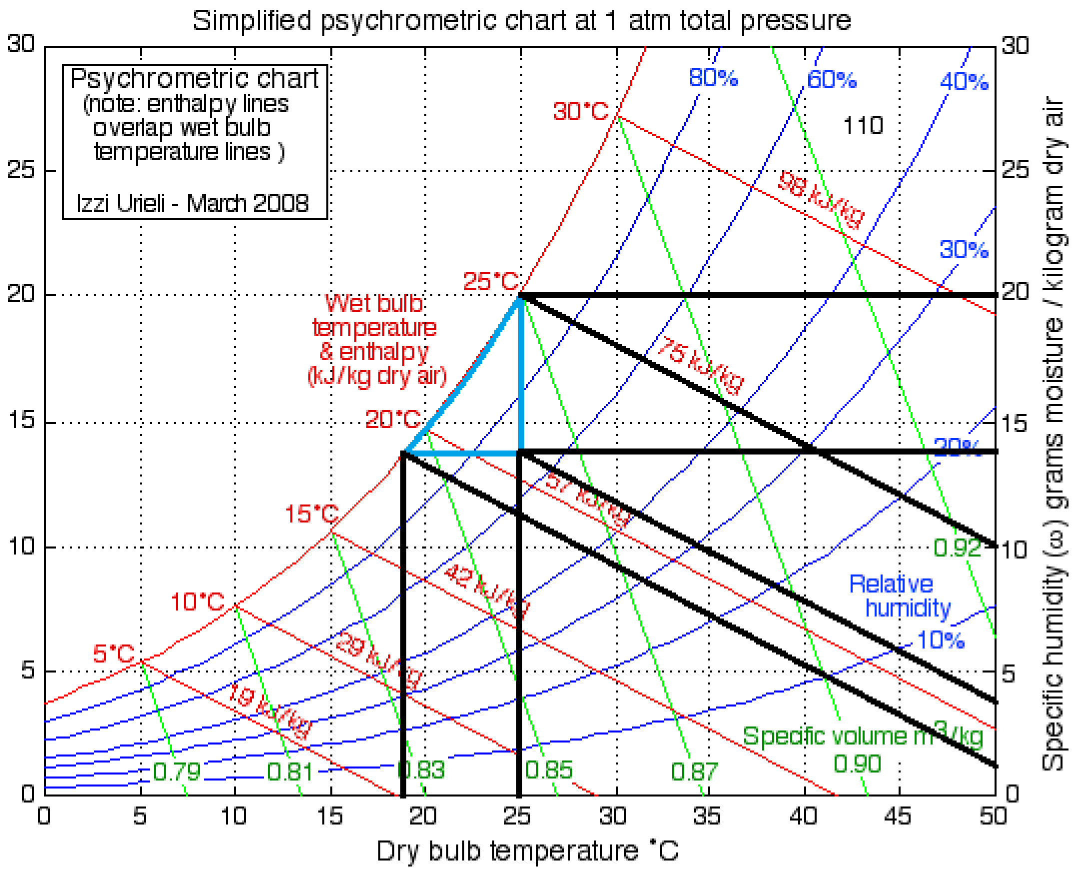


Figure 36: A psychrometric chart for sea-level elevation [24]

For design purposes, a 100% margin is included, leading to a refresh rate of 0,536 times per minute. For the total Vertical Farm, there is 92.718 m^2 of plant cultivation area, which corresponds to an air volume of 94.294 m^3. A refresh rate of 0,536 times per minute for this total volume results in a flow rate of 50.542 m^3/minute, or about 842 m^3/s, for the entire Vertical Farm. The three Environmental Control Floors each need to handle about a third of this, meaning 280,79 m^3/s.

With the four sections of the Environmental Control Floors each dealing with a quarter of the air flow, the sections should be designed to handle a flow of 70,2 m^3/second.

9.3.2 Heating and Cooling

The dehumidifier plates work by condensation of the water vapor 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.

The cycle which the air undergoes is indicated by blue lines in Figure 36. Starting from the cross-section of the 25 degrees Celsius dry bulb temperature and the 70% RH line, the humidity rises (vertical blue line). Then the air is cooled and the dry bulb temperature and humidity ratio decrease (curved blue line). Finally, the air is heated to the original temperature (horizontal blue line). The black lines indicate various important parameters, such as humidity ratio (horizontal black lines), dry bulb temperature (vertical black lines) and enthalpy (sloped black lines).

Here it is assumed that the air coming into the dehumidifier plates is at 25 degrees Celsius dry bulb temperature, with 100% RH. By using the psychrometric chart shown in Figure 36, 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 degrees Celsius dry bulb temperature is about 0,0138 grams 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 degrees Celsius 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 19 degrees Celsius.

Cooling the air from 25 degrees to 19 degrees Celsius at a at RH of 100%, means a reduction in enthalpy of the air from about 75 kJ/kg to 53,3 kJ/kg. Combine this with a flow rate of 280,79 m^3/second, and a density of 1,1839 kg/m^3 gives a total amount of energy removed from the air equal to: 7,22 MJ/s per floor.

Part of this energy can be used to re-heat the air to the desired 25 degrees. This would require an increase in enthalpy from 53,3 kJ/kg to about 60,3 kJ/kg, which corresponds to: 2,33 MJ/s per floor. Thus in total, 4,89 MJ/s of heat needs to be removed from each Environmental Control Floor and 14,7 MJ/s from the entire Vertical Farm.

9.3.3 Environmental Control System Sizing

The main components of the Environmental Control Floors are the fans and the heat exchangers. Based on the calculations done previously, it is possible to determine the required capacity and the expected power consumption of the fans and the heat exchangers.

Fans

Each Environmental Control Floor needs to handle an air volume flow of 280,79 m^3/second. To achieve this, there are six large central fans in the center of each Environmental Control Floor, which force the dry air down towards the Plant Cultivation Floors.

The fan type which was selected is the MPV-D1 1600 by Nyborg [25], see Figure 37. A performance diagram for this fan can be found in Appendix A.1.

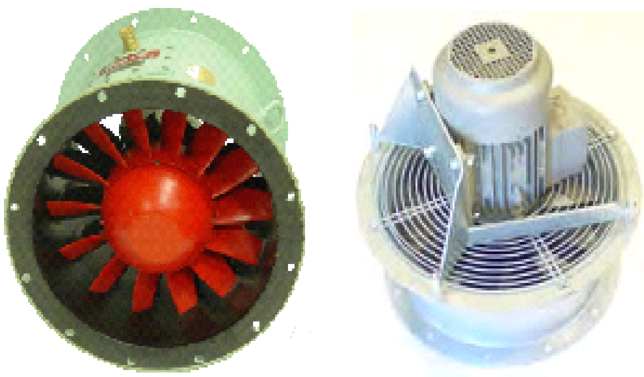


Figure 37: Nyborg MPV Axial and Vane-Axial Fans

Based on the diagram, the MPV-D1 1600 would use roughly 54 kW (without losses) to handle 50 m^3/s. The air velocity would be around 25 m/s and the fan rotation speed around 890 rpm. The static pressure added would be about 550 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 actual fans will be custom designed and could thus differ significantly from the above mentioned fans with regards to their performance.

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 between 7,8 and 8,77 m^3/s depending on the number of corresponding Plant Cultivation Floors (eight or nine). The duct fan selected for placement in the ducts is the MPV-A 710 [25]. For a volume of 9,0 m^3/s, it can be determined from the diagram in Appendix A.2 that the fans would use a minimum of 5,2 kW (without losses), while increasing the dynamic pressure by about 200 N/m^2. There are four ducts leading up to an Environmental Control Floor per Plant Cultivation Floor, with four inlet fans at the Plant Cultivation Floors and four outlet fans at the Environmental Control Floors, for a total of two-hundred of these duct fans.

For the two exhaust/inlet 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 280,79 m^3/second, so 140,4 m^3/second. For the expected power consumption of one of these fans, the combined power consumption of three of the fans in the center of the environmental floor is taken, and this is multiplied by a factor of 1,4 to obtain a power consumption of 227 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 average efficiency of 80% as discussed above in this chapter [22].

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 21.

<u>Heat exchangers</u>

As mentioned above there are two heat exchangers per Plant Cultivation Floor, which will be sized to handle 200 kW of cooling. Two heat exchangers per Plant Cultivation Floor result in 50 in total. Thus a COP of 4, the heat exchangers on the Plant Cultivation Floors will require 50 kW of power.

There are four heat exchangers on each of the Environmental Control Floors, which have to remove 4,89 MW of heat from the air. Thus, each of the heat exchangers needs to remove about 1,22 MW.

As mentioned, 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 four times lower than the cooling load of the heat exchangers. Thus, the heat exchangers on the Environmental Control Floors will use 305,8 kW.

The heat dissipation units on the roof need to dissipate all the heat from the Plant Cultivation Floor air (14,7 MW) and the LEDs (4,2 MW), which amounts to 18,9 MW. There are 32 heat dissipation units, so each needs to handle 590,63 kW. Assuming, as mentioned, a COP of 4, this means that each unit consumes about 148 kW.

The power and energy consumption of the heat exchangers can be found in Table 21. The LED heat exchangers are included here for completeness.

Table 21: Power and Energy consumption of the Environmental Control System

Component	Units [-]	Peak power per unit [kW]	Total power [kW]	Daily Operation time [h]	Daily Energy Consumption [kWh]
Duct fan	200	6,5	1.300	24	31.200
Central fan	18	67,5	1.215	24	29.160
Exhaust/Inlet fan	6	283,8	1.702,8	3	5.108,4
LED Plant Cultivation Floor heat exchangers	50	50	2.500	24	60.000
Environmental Control Floor heat exchangers	12	305,8	3.669,6	24	88.070,4
Roof heat dissipation units	32	148	4.736	24	113.664
Total	**-**	**-**	**15.123,4**	**-**	**327.202,8**

9.4 Equipment List

To obtain a cost estimate for the environmental control system an overview of the required equipment is generated. Based on comparable commercial systems, or rough estimation, prices are determined for the equipment, leading to an eventual cost for the entire system. The results can be seen in Table 22.

Table 22: Initial cost estimation of the equipment of the three Environmental Control Floors [FY12]

Equipment	Units [-]	Price [€/unit]	Total [k€]
Duct Fans	200	1.000	200
Central Fans	18	10.000	180
Exhaust/Inlet Fans	6	7.500	45
Duct system (for all Plant Cultivation Floors)	25	50.000	1.250
Piping	-	-	250
Dehumidifier plates	400	5.000	2.000
Heat exchangers	12	8.000	96
Water buffer tanks	12	2.500	30
Trace gas filter	12	15.000	180
Cooling fluid tanks	2	3.000	6
Cooling fluid pumps	6	30.000	180
Heat dissipation units	32	20.000	640
Total set-up costs			**5.057**
Margin of 20%			**1.011,4**
Total set-up costs with 20% margin			**6.068,4**

Note that the components of the environmental control system which are located on the Plant Cultivation Floors and the Waste Management Floors are considered in the equipment lists in the chapters discussing those floors.

10 Food Processing

Mature fish and full-grown plants are removed from their respective fish tanks and grow units, before being delivered to the Food Processing Floor. On the Food Processing Floor the fish and plants are inspected to ensure a proper quality product, before being prepared and packaged for delivery to supermarkets and restaurants.

10.1 Assumptions

No specific assumptions were made for the design of the Food Processing Floor. For the Supermarket and Delivery Area on the ground floor, it is assumed that the supermarket will be operated by an independent party, rather than the VF owner. As such, no equipment list or cost estimation is taken into account for the supermarket.

10.2 System Description

Based on the primary function of the Food Processing Floor, a floor design was made, as seen in Figure 38. Aside from rooms for fish and crop processing, it was found that there was excess space, which could be used for offices, a break room for the employees and an observation room to monitor the floors of the Vertical Farm. All the inedible biomass, fish and crops, is thrown in the waste chute, which runs directly down to the Waste Management Floors.

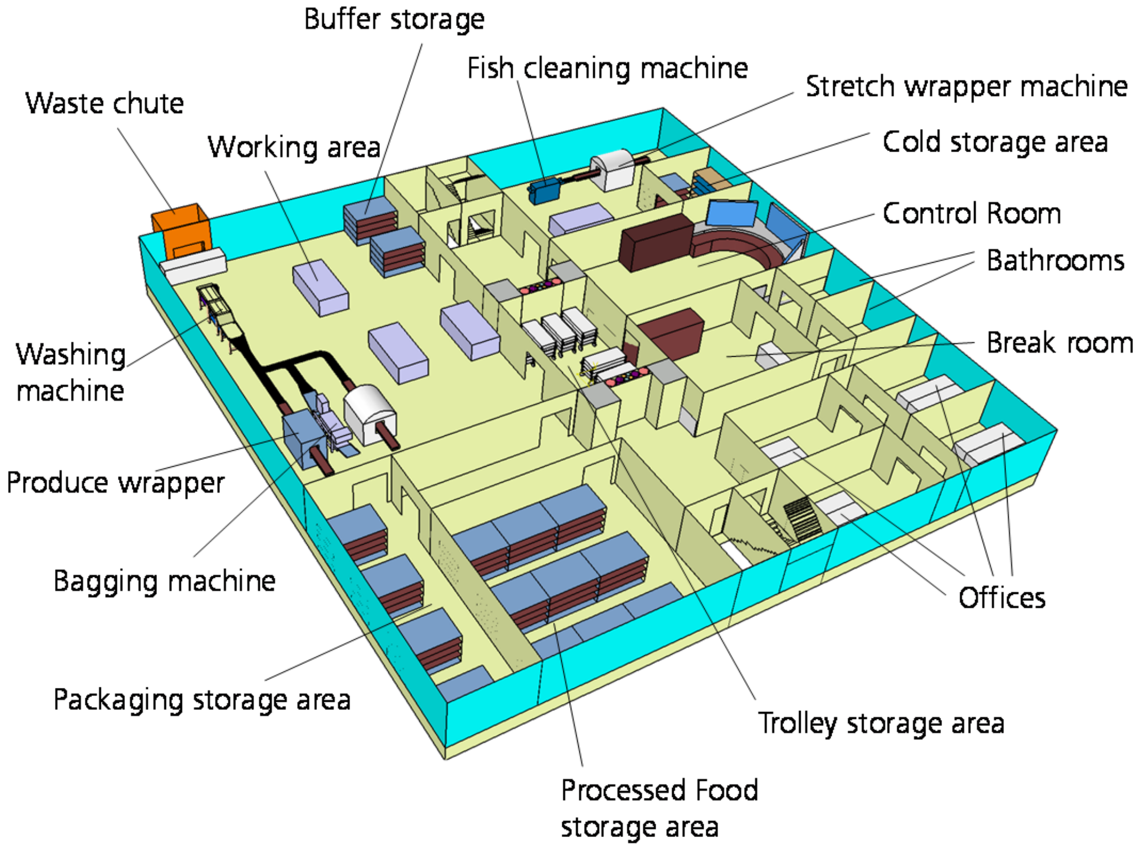


Figure 38: CATIA drawing of the Food Processing Floor.

The center of the floor contains a small room for trolleys, which can be used to move edible and inedible biomass around the rooms and to the floors. These can also be used to deliver the packaged food to the supermarket on the ground floor of the Vertical Farm, see Figure 39.

The ground floor contains the supermarket as mentioned. It also has a main entrance area. This area will also be used by the forklift trucks to move waste from the Waste Management Floors out of the building. Additionally, deliveries of equipment and goods and outgoing shipments of food will be processed in this area.

The waste chute is made visible in the supermarket storage area in Figure 39, but in reality, it will run between the external wall of the building and the internal building wall. It is envisioned that no waste will be dumped in the waste chute on this Supermarket and Delivery Area floor.

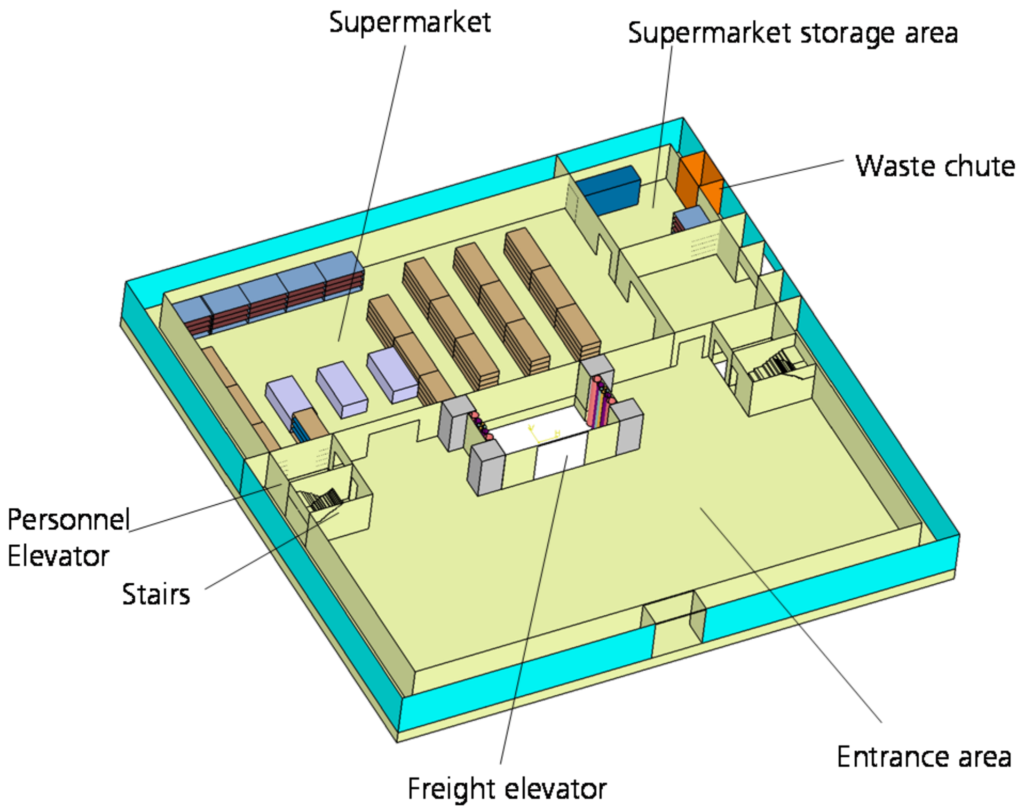


Figure 39: Ground Floor design

The Food Processing Floor has to process fish, as well as crops, such that the final product can be sold for consumption to the general public. For fish, this means washing and cutting the fish into filet, before packaging and cooling.

For crops, food processing starts with removal of the crops from the Grow Pallets. Then, after cleaning, the edible and inedible parts are separated. Finally, the edible vegetables and fruits are packaged, either individually or in some predetermined quantity. The inedible biomass resulting from the processing of fish and crops can then be delivered to the Waste Management Floors. Food, be it fish or crop, is brought to the floor through the elevators at either side. Depending on the quantity of food, it might be necessary to temporarily store it in the buffer storage, before it can be processed.

The edible fish is placed in the fish cleaning machine, which removes the entrails, scales and other unwanted parts. The remainder of the fish, the edible part, goes through the stretch wrapper machine, resulting in packaged fish, which is ready to be sold. The packaged fish is then temporarily stored in a cold storage area, before it is delivered to the supermarket in the Vertical Farm.

The edible vegetables and fruits are placed in a washing machine for cleaning, before being delivered to packaging machines. Depending on the type of crop, it may go through the bagging machine, the produce wrapper or a stretch wrapper machine. Then, after packaging, the food is temporarily stored in the processed food storage area. Figure 40 shows examples of a washing machine and a stretch wrapper packaging machine which could be used in the Vertical Farm.

Figure 40: (left) Polywash™ Multi-Produce Washer [Source: Meyer Industries, Inc.] (right) Stretch Wrapper packaging machine [AES-Sorma Ltd.]

10.3 Equipment List

Based on the design of the Food Processing Floor, as seen in Figure 38, it is possible to create a list of required equipment and costs based on best engineering estimates. This list can be found in Table 23.

While a supermarket has been indicated in Figure 39, it is assumed that this will be operated by an independent party, rather than the Vertical Farm owner. As such, no equipment list or cost estimation is taken into account for the supermarket.

Table 23: Initial cost estimation for the Food Processing Floor equipment [FY12]

Equipment	**Units [-]**	**Price [€/unit]**	**Total [k€]**
Polywash™ Multi-Produce Washers	2	45.000	90
Roll Stock Poly Baggers	2	30.000	60
Stretch Wrappers	4	35.000	140
Produce Wrappers	2	35.000	70
Conveyors	4	3.000	12
High-end Computer / Control Unit	2	4.000	8
Fish cleaning machine	2	15.000	30
Office computer	10	1.000	10
Packaging storage closet	4	250	1
Food storage closet	12	250	3
Cold storage closet	2	500	1
Office desks	10	500	5
Working tables	5	1.000	5
Control Room Data center	1	17.500	17,5
Control Room monitors	10	3.000	30
Tables	2	500	1
Kitchen / Break area	1	7.500	7,5
Trolleys	20	100	2
Total set-up costs			**493**
Margin of 20%			**98,6**
Total set-up costs with 20% margin			**591,6**

11 Waste Management

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 solid fish waste (e.g. fish heads, bones) from the fish farms.

The annual waste produced by the plant growth floors of the Vertical Farm was calculated to be roughly 3.420 metric tons per year. The waste (e.g. faeces, fish bones) produced by the fish farms was determined to be about 394 tons per year. Since it was assumed in chapter 6 that 1.000 kilograms of plant waste is used as fish feed each day, the total remaining waste is roughly 9,45 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. The design for the Vertical Farm incorporates two Waste Management Floors, which do exactly that.

11.1 Assumptions

Certain assumptions were made during the design study and the relevant ones for the Waste Management Floors are listed below:

- It is assumed that only the inedible biomass from the fish farms and the Plant Cultivation Floors needs to be processed. Any packaging waste or broken equipment is not handled by this system. Additionally, it is assumed that no edible biomass needs to be discarded due to e.g. defects or disease.
- It is assumed that 1.000 kilograms per day of inedible plant mass is used as fish feed, rather than ending up on the Waste Management Floors.
- It is assumed that all of the waste on the Waste Management Floors is used for biogas production.
- It was assumed that a fertilizer facility will be used to extract nutrients from the plant and fish waste and deliver these nutrients to the Nutrient Delivery System. The equipment and estimated cost for the fertilizer facility have been taken into account, but the calculations on the amount of fertilizer which can be recovered have been left for future studies.
- A conservative value was used to calculate the biomass yield of the Plant Cultivation Floors. As such, the actual edible and inedible biomass output may be higher than calculated. To be able to cope with the potentially higher than average waste production, the biogas digesters will have a design capacity of 6.900 metric tons per year. This is roughly twice the average value.

11.2 System description

The Waste Management Floors can be used for biogas production and nutrient recovery from waste. For the purposes of this design study, only the biogas production through Anaerobic Digestion (AD) is calculated. First, the designs for the Waste Management Floors are presented and discussed, after which a brief description of the AD and nutrient extraction processes is given.

11.2.1 Waste Management Floor design

Figure 41 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 buffer storage container.

From this large storage container, smaller waste containers (max. one ton) are filled. These smaller waste containers are then moved around using forklift trucks to either the biogas domes, or the fertilizer facility.

As mentioned previously, the biogas domes, with connected buffer tanks, are used to convert bio-waste into biogas. Each biogas dome has a reserved space which is left open to allow easy movement of a forklift truck, which is used to transport up to one ton of waste at a time.

The forklift trucks move waste from the large storage container to the biogas domes, or the mixing tank and fertilizer facility. Also, the trucks are used to move digestate and left-over waste out of the building.

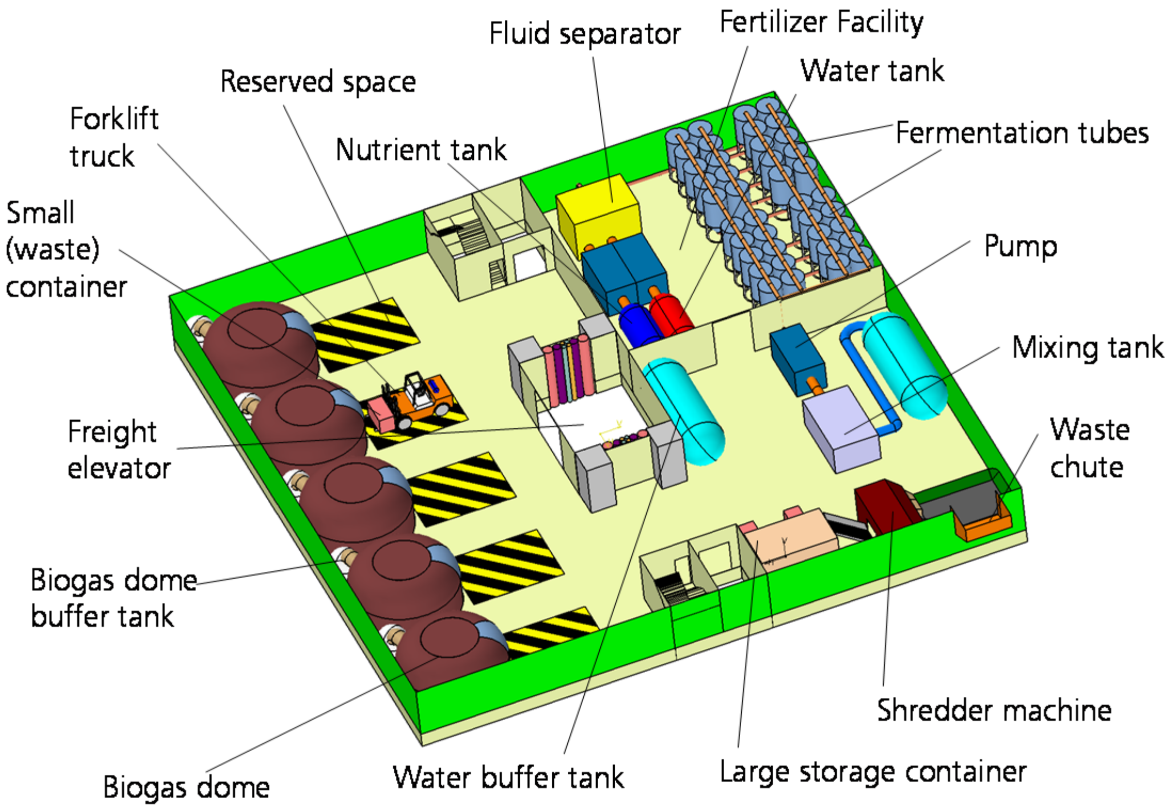


Figure 41: Waste Management Floor 1 layout

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 biogas 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 42, also has biogas domes, like the first floor. The remaining part of the floor is used for gas storage and power generation. Gas from the biogas domes is led into a gas separation unit, with two gas separation membranes. Here, the biogas 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.

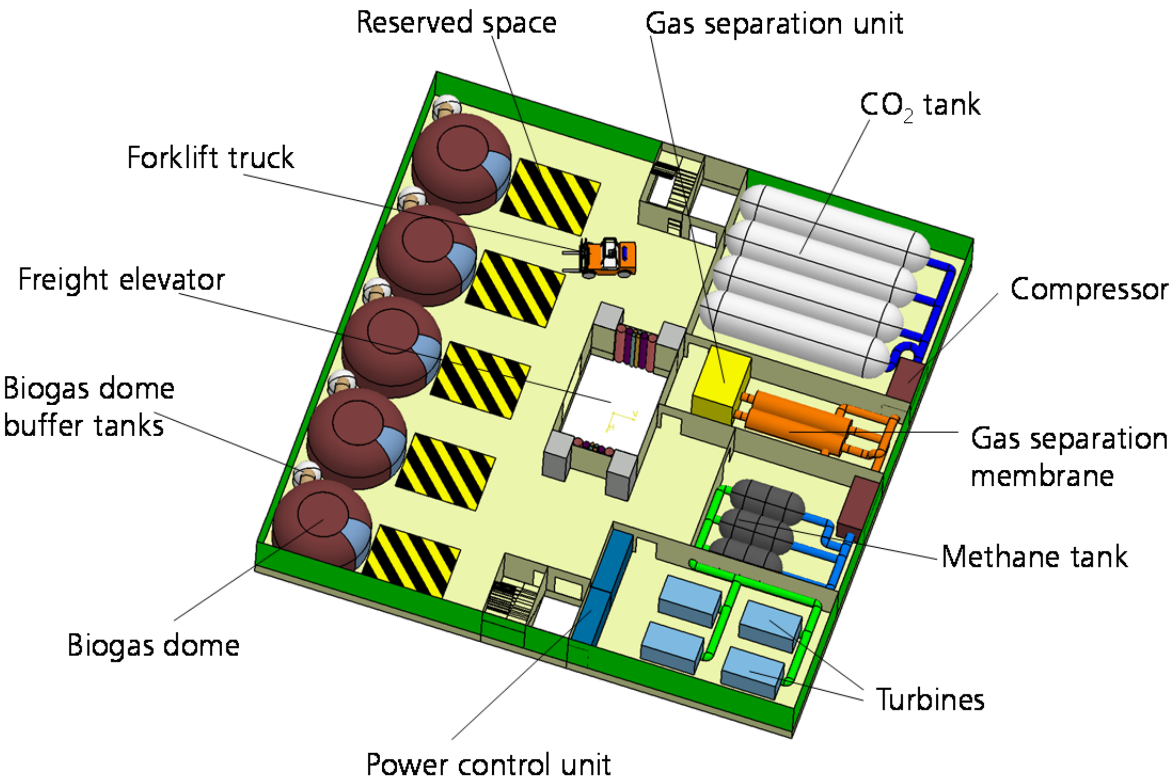


Figure 42: Waste Management Floor 2 layout

Having discussed the design of the Waste Management Floors, a brief overview of the biogas production and nutrient extraction processes will be given, before some calculations are performed.

11.2.2 Anaerobic Digestion

Anaerobic Digestion (AD), see Figure 43, is a mature technology to produce biogas from solid waste [26]. The AD process breaks down the organic content (e.g. cellulose, lignin) in the waste into biogas with the help of microbial activity. The process uses a variety of bacteria and microbes to break down the complex organic molecules into biogas.

As can be seen in Figure 43, the AD process occurs in four stages: Hydrolysis, followed by acidogenesis, acetogenesis and finally methanogenesis. 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 biogas end-product [26]. 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 archaea 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.

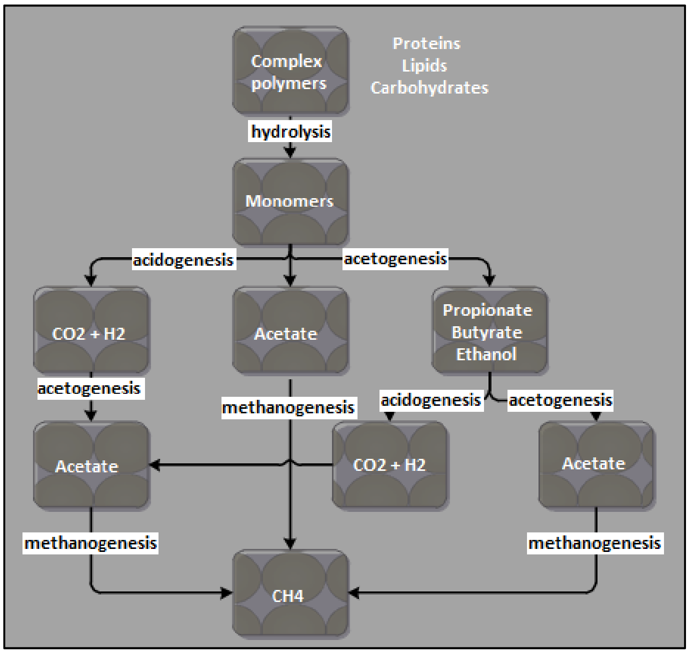


Figure 43: Anaerobic Digestion Process diagram [27]

The specific biogas 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” [28].

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 biogas/methane yield per unit of waste. This is the result of more efficient waste digestion by the anaerobic bacteria and micro-organisms.

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 biogas generation process is complete.

The amount of digestate, which is produced by an AD reactor can range from 20 - 40% of the total waste material delivered to the digester [29].

This digestate consists of the waste which cannot be processed by the bacteria used in the AD process, as well as some fraction of the waste which remains after undergoing the AD process.

11.2.3 Nutrient extraction process

The nutrient extraction process is based on pumping a mixture of shredded inedible biomass and water, 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.

For the current study, the possibility of nutrient extraction has been considered, and the equipment which would be needed has been taken into account in the cost estimations, but lacking sufficient data on the performance of the process, no calculations were performed to determine the amount of nutrients which can be recovered. This shall be investigated in later studies. Instead, all the calculations performed for the waste management, assume that all the waste on the Waste Management Floors is used for biogas production.

11.3 Bio-waste treatment

Based on information from literature on the AD process, it is possible to determine the amount of biogas which can be produced in the Vertical Farm. As mentioned earlier, no initial calculations were done on the amount of nutrients which can be extracted. It is assumed that all the waste is processed to generate biogas using the AD treatment.

The amount of biogas which can be produced from bio-waste is determined from Figure 44, which shows the biogas yield in m^3 per ton of Volatile Solid (VS), versus the Organic Loading Rate (OLR). Volatile Solids are the portion of organic-material solids which can be digested by the bacteria and micro-organisms present in the digester [30].

Combining the data from Figure 44, with specific numbers for the amount of VS and the OLR, makes it possible to determine the total biogas yield.

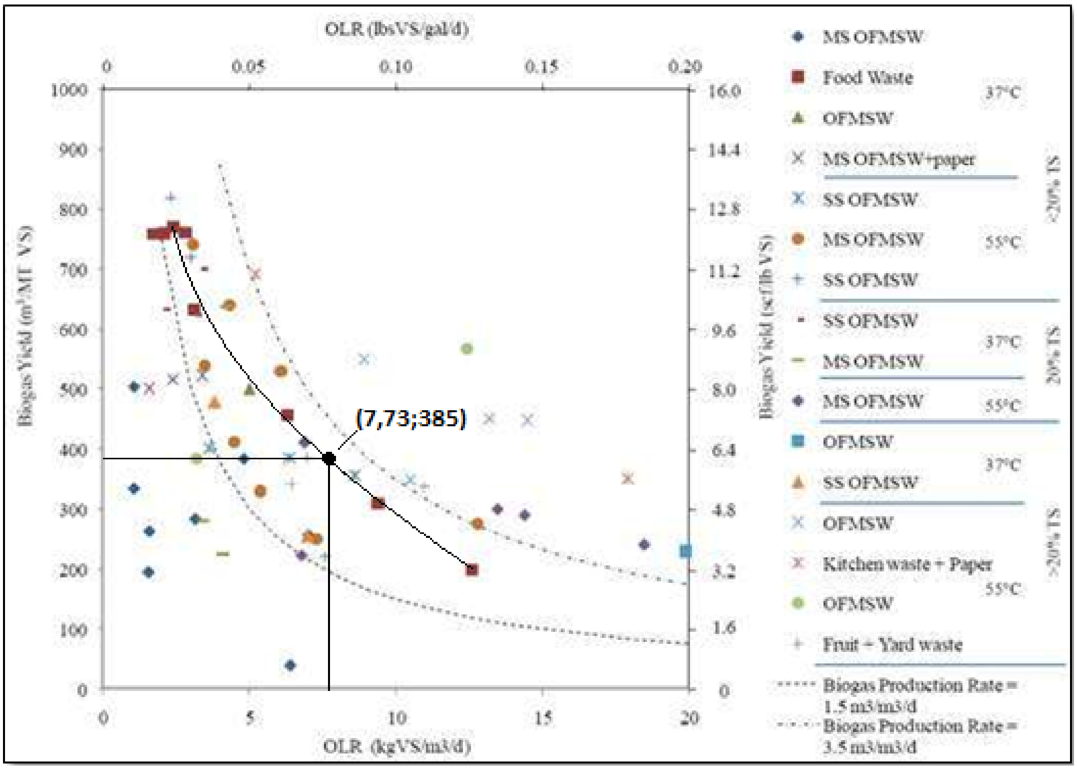


Figure 44: Anaerobic Digestion Biogas Potential [27]. *(Sorry for the bad quality)*

Based on information for CROPGEN [31], the Volatile to Total Solid (TS) ratio is presented in Table 24 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. For ease of calculations an average value of 90% will be used for the Volatile to Total Solids ratio of the combined plant and fish waste.

It was mentioned earlier that on average the amount of waste coming into the Waste Management Floors each day is 9,45 tons. Since 90% of the Total Solids is Volatile Solids, the Vertical Farm produces about 8,51 tons of VS per day.

The Waste Management Floors have ten digesters (biogas domes), each with a volume of 110 m^3, leading to a total digester volume of 1.100 m^3. The OLR can then be calculated to be: 8.505 kg VS/ day / 1.100 m^3 is: 7,73 kg VS/m^3*day.

From Figure 44, by drawing a rough line through the data points for Food Waste (curved black line), it can be found that for an OLR of 7,73 kg VS/m^3*day, the biogas yield is about 385 m^3/MT VS. This is comparable to biogas yields reported in [32]. 8,51 tons of VS per day times 385 m^3 biogas per metric ton of VS results in 3.276 m^3 of biogas per day.

A higher total digester volume would make it possible to have a lower OLR, but would increase equipment cost and operating cost. Furthermore, the available space per floor also acts as a limiting factor.

Table 24: Volatile Solid to Total Solid ratio for the VF crops [31].

Crop	VS/TS [%]
Lettuce	91,5
Cabbage	91,5
Spinach	91,5
Carrots	91,4
Radish	83,3
Tomatoes	95,3
Peppers	95,3
Potatoes	92,5
Peas	90,0
Strawberries	91,5

To determine the amount of methane and carbon dioxide production from the biogas yield, the specific composition of the biogas should be determined. Table 25 lists the average composition of biogas 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 biogas consists of 60% methane gives a production of 1.966 m^3 of methane gas per day. Additionally, using the assumption that 30% of the biogas is carbon dioxide, the Waste Management Floor produces 983 m^3 of CO_2 per day.

The power which can be generated with this amount of methane gas is discussed in Chapter 12.

Table 25: Average biogas composition [33].

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)	1-3

Any left-over waste after either biogas production or fertilizer extraction is sold or a third party is paid to pick up this rest waste and process it further.

11.4 Equipment List

Based on the components needed for the anaerobic digestion process, as well as the nutrient extraction process, and taking into account the design of the Waste Management Floors as seen in Figure 41 and Figure 42, it is possible to create a list of the equipment needed for the Waste

Management Floors. A best estimate is then made for the equipment cost, allowing for a first approximation of the required start-up investment. This can be seen in Table 26.

The capital cost for the biogas digesters is (roughly) estimated based on Figure 45, which shows capital cost for anaerobic digesters versus design capacity.

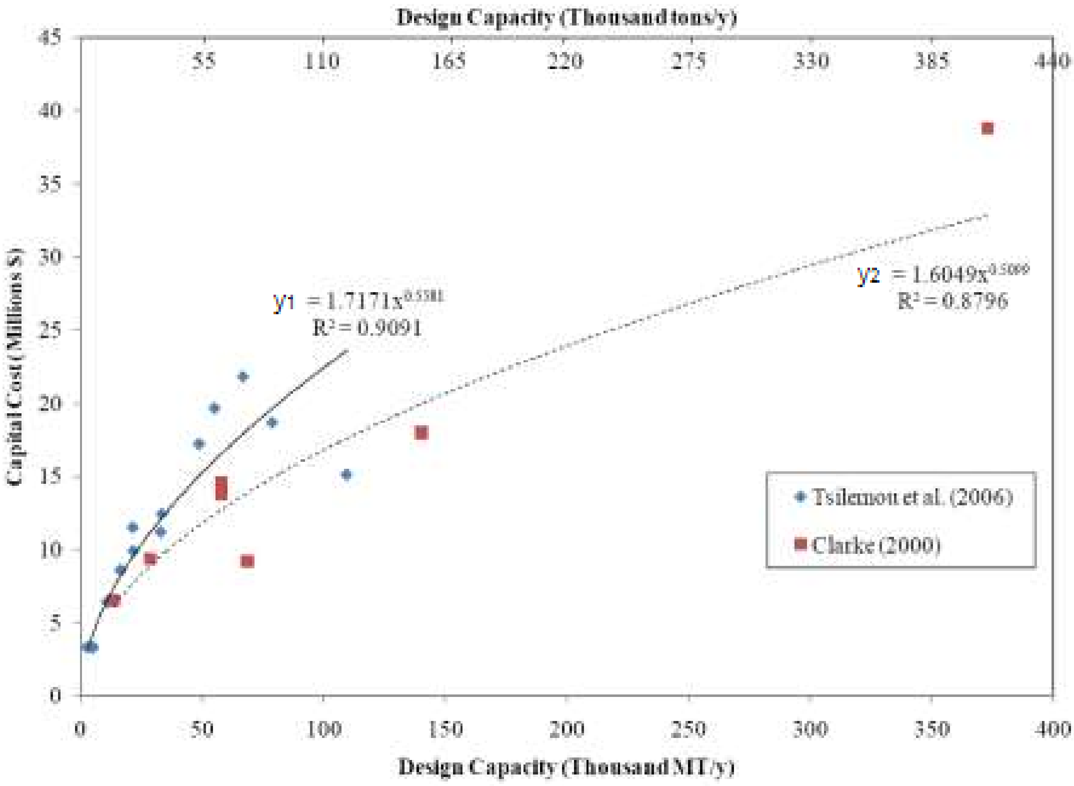


Figure 45: Capital Cost versus Design Capacity for anaerobic digesters [27] *(Sorry for the bad quality)*

Two lines are indicated in Figure 45, each with a corresponding equation, both of which are stated below:

$$y_1 = 1{,}7171 * x^{0{,}5581},$$
$$y_2 = 1{,}6049 * x^{0{,}5099}.$$

On average the ten anaerobic digesters (biogas dome) have to process $3{,}45*10^3$ MT/year of waste. The actual waste produced may be higher, since a conservative estimate was used for the biomass yield. To ensure that the biogas digesters have sufficient capacity, the design capacity of the digesters will be twice the average value, so $6.9*10^3$ MT/year. Filling in this number into the two formulas given above and then taking the higher of the two costs, it is possible to calculate that the biogas digesters will cost approximately 5.000 k€ [FY 2012].

Table 26: Equipment list and cost estimation for the Waste Management Floors [FY12]

Equipment	Units [-]	Price [€/unit]	Total [k€]
Biogas digesters	10	500.000	5.000
Fermentation tanks	40	40.000	1.600
Fork lift truck	2	30.000	60
Pipes	-	-	300
Methane storage tanks	3	5.000	15
CHP generators / Turbines	4	10.000	40
Large Waste storage tank	1	3.000	3

Equipment	Units [-]	Price [€/unit]	Total [k€]
Shredder machine	1	10.000	10
Water buffer tanks	2	5.000	10
Compressors	2	10.000	20
Gas separation unit	1	50.000	50
Gas separation membrane	2	15.000	30
Power Control Units	2	15.000	30
Pumps	3	5.000	15
Small Waste storage tank	6	750	4,5
Mixing tank	1	1.000	1
Nutrient tank	1	5.000	5
Water tank	1	5.000	5
Carbon dioxide tanks	4	10.000	40
Carbon dioxide regulators	100	250	25
Total set-up costs			**7.263,5**
Margin of 20%			**1.452,7**
Total set-up costs with 20% margin			**8.716,2**

12 Economic Analysis

In this chapter the capital expenditure for constructing and operating a VF is discussed. These costs are divided in non-recurring and recurring costs. The non-recurring costs pertain to the costs of the building and the internal equipment. Recurring costs embrace cost items like for example personnel, power or water demand. The chapter concludes with a profitability analysis of the VF illustrated in previous chapters.

12.1 Global Cost Assumptions

The following global assumptions were made to estimate the overall VF costs:

- With respect to the Phase-A accuracy there will be a margin on each cost item of 20% in order to reflect a certain risk.
- Costs are displayed in FY 2012.
- Non recurrent costs amortised over a period of 30 years
- Rate of interest i is assumed with 3% for the next years.
- Assumed currency conversion rate 1,30 US$/€
- Any left-over waste after either biogas production or fertilizer extraction is sold or a third party is paid to pick up this rest waste and process it further. This cost item is not considered in the cost estimation of this chapter.

12.2 Non-Recurring Costs

12.2.1 Building Cost Estimation Approach

The cost estimate of building construction or renovation is based on the cost of building construction data base of Baukosteninformationszentrum (BKI) [34]. 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 German Chambers of Architects 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 (see Table 53 to Table 55 in Appendix B).

The required data is derived from actual construction costs or cost estimation of architectural firms through statistical averaging. In this context, cost parameters describe the relationship between the costs of certain categories (according to DIN 276-1:2008-12) 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 [34]. The planning parameters describe the mutual relationships of certain areas and volumes. They are used in the form of percentages or 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 cost estimation of the building construction costs is done by breaking down the overall structure into smaller components, on several levels and matching them with the KKW & PKW. The first level of the building cost breakdown is structured into the following seven groups:

- 100: Site (e.g. value of estate, additional fees)
- 200: Opening up (e.g. preparation, public opening)

- 300: Building – Construction (e.g. excavation, foundation)
- 400: Building – Technical plants (e.g. sewage, water, gas plants)
- 500: Outdoor Facility (e.g. water area, paved area)
- 600: Building infrastructure equipment (e.g. general equipment)
- 700: Additional building costs (e.g. assessment and advice, finance costs)

To get a more accurate cost estimation the first level of the 300 and 400 cost group is broken down into the second level. The following example shows the second level of group 300:

- 300: Building:
  - 310: Excavation
  - 320: Foundation
  - 330: Outer walls
  - 340: Inner walls
  - 350: Ceiling
  - 360: Roof
  - 370: Constructional installations
  - 390: Construction area

The results of the final estimate for the Vertical Farm are described in the following subchapter.

12.2.2 Building Cost Estimation

The following assumptions were made to estimate the building construction costs:

- First level of the 300 and 400 construction cost group is broken down into the second level of Din 276.
- The new VF building is simplified to a model, so a parametric estimate can be performed. The real building may verify from the simplistic model.
- The cost calculation is divided into the estimation of the building shell and the estimation of one exemplary floor, which is then multiplied by 37 (amount of floors).
- Building shell (excavation, foundation, outer wall, roof, site and opening up, outdoor facitlity) → type *industrial production building, mainly skeleton structure*, BKI with publication date of 2011 [34]:
  - Plot area / site of (FBG): 2.500 m² (50 x 50 m²)
  - BGF: 1.936 m² (44 x 44 m²)
  - Excavation: 45.496 m³ (44 x 44 x 23,5 m³)
  - Foundation: 1.936 m² (44 x 44 m²)
  - Outer wall: 29.480 m² (167,5 x 44 x 4 m²)
  - Roof: 2.000 m²
- One Exemplary floor → type *industrial production building, mainly skeleton structure*, BKI with publication date of 2011 [34] (w/o excavation, foundation, outer wall, roof, site and opening up):
  - Inner walls (average): 690 m²
  - Ceiling: 1.936 (44 x 44 m²)
  - Floor-to-floor height: 4,5 m (exception is the 5th basement with 5,5 m)
- No internal infrastructure for plant or fish cultivation/processing within the building equipment was estimated in this subchapter. (see subchapter 12.2.3 for detailed equipment cost estimation)
- The price of the site were estimated through the average costs per m² in Berlin of 229 €/m² [35].

- The maximum cost parameter values for the *industrial production building, mainly skeleton structure* were chosen in the cost estimation with respect to the height of the building.

With the help of the displayed assumptions the following estimation of the building costs was drawn up. Table 29 shows the estimated costs of the outer shell of the VF. The overall costs of the shell are 13 M€ (FY 2012) without margin.

Table 27: Detailed cost simulation model "shell" [FY12]

Cost Simulation Model industrial production building, mainly skeleton structure "Shell"										
KG Cost groups to the 2nd level	unit	Quantities with Planning parameters				Cost variables				Costs (FY12)
			average		chosen	min	average	max	chosen	
Calculation Method:		FBG			FBG		KKW €		chosen	Costs €
100 Site	m² FBG	2500				0,00	229,00	0,00	229,00	589.675,00
100 Site									Σ100:	589.675,00
200 Opening up	m² FBG	2500				5,00	10,00	16,00	16,00	41.200,00
200 Opening up									Σ200:	41.200,00
Calculation Method:		BGF	PKW/BGF	simulation	chosen		KKW €		chosen	Costs €
310 Excavation	m³ BGI	1936	1,14	2.207,04	45.496,00	11,00	22,00	34,00	34,00	1.593.269,92
320 Foundation	m² GRF	BGF for all rows	0,70	1.355,20	1.936,00	154,00	217,00	326,00	326,00	650.070,08
330 Outer wall	m² AWF		0,48	929,28	29.480,00	224,00	258,00	301,00	301,00	9.139.684,40
360 Roof	m² DAF		0,71	1.374,56	2.000,00	147,00	192,00	255,00	255,00	525.300,00
310, 320, 330, 360 Building - Construction									Σ310 320 330 360:	11.908.324,40
Calculation Method:		AUG			AUG		KKW €		chosen	Costs €
500 Outdoor Facility	m² 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:	12.539.199,40

In Table 28 the total cost with an amount of 3 M€ (FY 2012) without margin for a single floor is shown.

Table 28: Detailed cost simulation model "1x floor" [FY12]

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				Costs (FY12)
			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	209.656,50
350 Ceiling	m² DEF	BGF for all rows	0,25	484,00	1.936,00	215,00	281,00	372,00	372,00	741.797,76
370 Constructional installations	m² BGF		1,00	1.936,00	1.936,00	0,00	13,00	25,00	25,00	49.852,00
390 Construction area	m² BGF		1,00	1.936,00	1.936,00	6,00	14,00	28,00	28,00	55.834,24
300 Building - Construction (w/o 310, 320, 330, 360)									Σ300:	1.057.140,50
410 Sewage, water, gas plants	m² BGF		1,00	1.936,00	1.936,00	20,00	25,00	33,00	33,00	65.804,64
420 Heat-supply systems	m² BGF		1,00	1.936,00	1.936,00	22,00	33,00	49,00	49,00	97.709,92
430 Air conditioning systems	m² BGF		1,00	1.936,00	1.936,00	6,00	15,00	30,00	30,00	59.822,40
440 High voltage plants	m² BGF		1,00	1.936,00	1.936,00	41,00	63,00	108,00	108,00	215.360,64
450 Com. and info. technology equip.	m² BGF		1,00	1.936,00	1.936,00	2,00	6,00	13,00	13,00	25.923,04
460 Conveyor systems	m² BGF		1,00	1.936,00	1.936,00	18,00	42,00	127,00	127,00	253.248,16
470 Plants for specific usage	m² BGF		1,00	1.936,00	1.936,00	18,00	75,00	297,00	297,00	592.241,76
480 Building automation	m² BGF		1,00	1.936,00	1.936,00	0,00	7,00	0,00	7,00	13.958,56
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:	1.324.069,12
Sum 300+400 (w/o 310, 320, 330, 360)									Σ300+400:	2.381.209,62
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	420.750,88
700 Additional building costs									Σ700:	420.750,88
Total costs industrial production building, mainly skeleton structure "1x Floor"									Σall:	2.801.960,50

The total costs of the VF with 37 floors are around 139 M€ (FY 2012) including a 20% margin (see Table 29).

Table 29: Building cost summary [FY12]

Cost Item	Total Cost [k€]
Shell of the VF	12.539
37 Floors of the VF	103.673
Total set-up costs	**116.212**
Margin of 20%	**23.242**
Total set-up costs with 20% margin	**139.454**

12.2.3 Initial Equipment Cost

In the chapters discussing the various subsystems and floor designs, lists of required equipment and estimated costs for that equipment were presented. By combining the equipment lists, it is possible to estimate the costs of the special equipment for the entire Vertical Farm.

The cost estimate based on best engineering estimates for the equipment needed for the subsystems can be found inTable 30 below. The costs are in k€ and have been rounded up. The total estimated cost for the equipment needed for the Vertical Farm is about 145 M€ (FY 2012) with 20% margin.

Table 30: Vertical Farm special equipment cost estimate [FY12]

Subsystem	Total Cost [k€]	Margin of 20% [k€]	Total Cost with 20% margin [k€]	Detailed overview in
Germination	2.000	400	2.400	Chapter 4.3; Table 4
Plant Cultivation	22.885	4.577	27.462	Chapter 5.5; Table 8
Fish Farming	1.311	262	1.573	Chapter 6.4; Table 12
Nutrient Delivery	8.478	1.696	10.174	Chapter 7.4; Table 14
Lighting	70.900	14.180	85.080	Chapter 8.5; Table 19
Environmental Control	5.057	1.011	6.068	Chapter 9.4; Table 22
Food Processing, Staff	493	99	592	Chapter 10.3; Table 23
Waste Management	7.264	1.453	8.716	Chapter 11.4; Table 26
Personnel Elevators (2x)	1.667	333	2.000	-
Freight Elevators (1x)	125	25	150	-
Central shaft piping	833	167	1.000	-
Total	**121.013**	**24.202**	**145.215**	

In addition to the equipment costs of the subsystems, two personnel elevators, and one small freight elevator for the Waste Management Floors and the piping for the central shaft have to be added to the internal structure of the VF. These costs can also be seen in Table 30.

12.2.4 Cost summary non-recurring costs

Total non-recurring costs for the VF were estimated to 285 M€ (FY 2012) with 20% margin (see Table 31).

Table 31: Cost summary non-recurring costs [FY12]

Cost Item	Total Costs [M€]	Margin of 20% [M€]	Total set-up Costs with 20% [M€]
VF building	116,21	23,24	139,45
VF special equipment	121,01	24,20	145,22
Total	**237,23**	**47,44**	**284,67**

It is assumed that the overall non-recurring costs will be amortized over a period n of 30 years, with no residual value to have the possibility to add them to the operational costs. For that reason the annuity a of the total non-recurring costs C_0 to be calculated by using the following annuity equation with a payout at the beginning of every year [36]:

$$a = \frac{C_0}{(1+i)} \cdot \frac{(1+i)^n \cdot i}{(1+i)^n - 1}.$$

As mentioned before the interest rate i has an amount of 3%. So the annuity cost for the whole VF non-recurring costs have an amount of 14 M€/a (see also Figure 46).

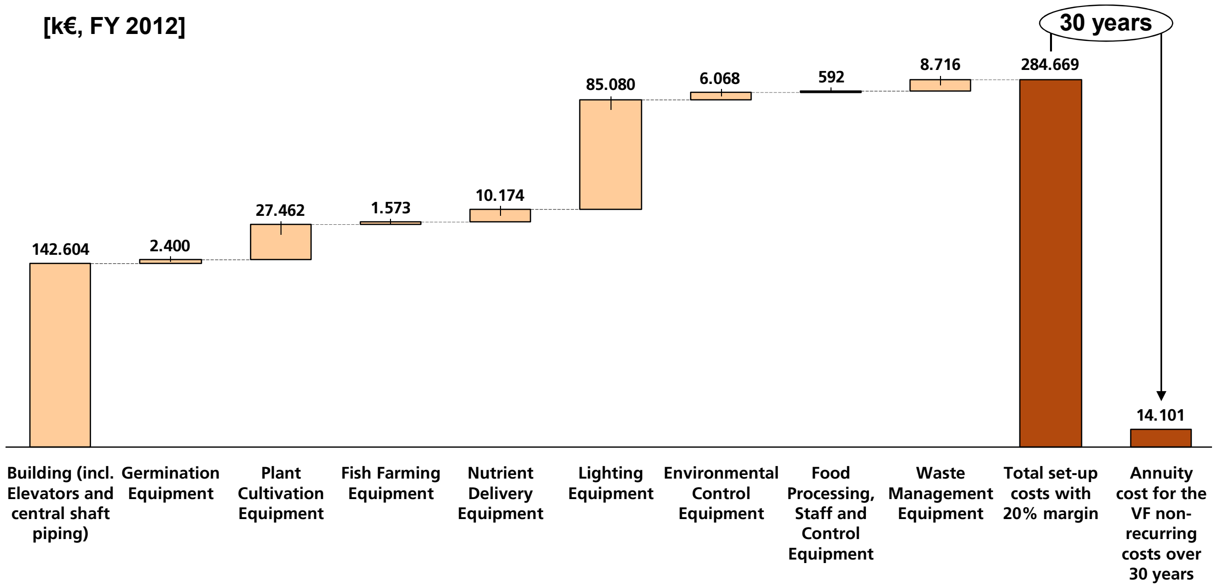


Figure 46: VF non-recurring costs [FY12] and annuity cost.

12.3 Recurring Costs

12.3.1 Power

The following assumptions were made to estimate the power costs:

- Conservative gross average industrial price for electricity in Germany of 0,16 €/kWh (FY 2012) including all taxes, charges, contributions and miscellaneous costs to consider rising power prices in the following years [37].
- Peak power and daily energy consumption values of the Environmental Control Floor and the Lighting System are taken from the calculations of chapters 9 and 8.
- All other values are assumed by best engineering estimate.
- 1.966 m³ methane gas are produced by the Waste Management Floor each day. The combustion of 1 m³ of methane at 15 °C (natural gas) releases energy of 9,89 kWh (35,6 MJ) [38]. An efficiency of 40% is assumed for the turbine generators.

Table 32 shows the estimated power and energy demands of the subsystems of the proposed Vertical Farm design.

Table 32: Summary of Power and Energy consumption of all subsystems

Subsystem	Peak power [kW]	Daily operation time [h]	Daily energy consumption [kWh]*	Total Cost [k€/a]**	Margin of 20% [k€/a]	Total Cost with 20% margin [k€/a]
Fish Farming	15	24	360	21,02	4,20	25,22
Waste Management	15	24	360	21,02	4,20	25,22
Food Processing, Staff and Control	38	-	252	14,72	2,94	17,66
Germination	150	24	3.600	210,24	42,05	252,29
Environmental Control	15.123	-	327.203	19.108,66	3.821,73	22.930,39
Nutrient Delivery	15	24	360	21,02	4,20	25,22
Lighting	5.931	-	81.124	4.737,64	947,53	5.685,17
Total			**413.259**	**24.134,32**	**4.826,86**	**28.961,18**
Turbine generator	-	-	7.776	**454,12**	90,82	544,94
Total Needed	**21.287**	**-**	**405.483**	**23.680,20**	**4.736,04**	**28.416,24**

* Based on constant peak power consumption during the operating times of the subsystems
** Based on gross average industrial price for electricity in Germany of 0,16 €/kWh (FY 2012) including all taxes, charges, contributions and miscellaneous costs

Assuming an conservative gross average industrial price of 0,16 €/kWh for electricity in Germany [37], the yearly energy cost for the VF comes out at 28.416 k€ (FY 2012) with 20% margin.

12.3.2 Equipment Replacement and Maintenance

The following assumptions were made to estimate the costs for maintenance and replacement of the VF equipment:

- The equipment has to be replaced every 10 years.
- For this purpose 10% of the initial equipment costs is set aside each year.

It is inevitable that the initial equipment bought for the Vertical Farm will eventually require maintenance or replacement. While this may not occur on a regular schedule, it is assumed here that a yearly sum of money is set aside to cover any and all expenses related to the maintenance and replacement of equipment. This corresponds to yearly costs of 14,5 M€ (FY 2012) with 20% margin.

12.3.3 Other Resources

The following assumptions were made to estimate the costs for other resources like seeds and water:

- Seed cost estimation based on the wholesale prices of seeds meant for the purpose of gardening.
- The costs of the nutrients required for the plant cultivation are based on the calculated consumption of Beyond™ fertilizer and its market price of 50$ per 474 ml [16].
- As mentioned earlier (see subchapter 7.3), it is assumed that all the water used in the VF, except for the plant cultivation system is recovered and re-used. For the Plant Cultivation Floor it was determined that a small percentage of the water used for plant growth could not be recovered (see Table 13). This amounted to 22.670 L of water per day

which cannot be recovered and thus needs to be brought into the VF. From [39] a water price of 0,00185 €/L could be found for Bremen (Germany).

- It is assumed that 1.000 kilograms of the fish feed requirements is met by waste from the Plant Cultivation floors every day. The rest of the feed requirements (360 kg/day) will be high-protein fish feed bought from an external supplier.
- The cost for high-protein fish food is taken to be 2,5 €/kg, which is roughly the average of the lowest (0,5) and highest (5) values found from [40].

The costs for the plant seeds are taken from [40] [41], which calculates a yearly cost of ca. 55 k€ (FY 2012) with 20% margin (see Table 33).

Table 33: Seed costs per year of the plant [FY12]

Seed Costs	Plant Density [plants/m²] [42]	Total Growing Area [m²] [6]	Growth period [d] [6]	Growth period Amount [periods/a]	Plants [plants/a]	Cost [€/seed] [40]	Total Cost [€/a]
Carrots	50,00*	7.344	75	4,87	1.787.040	0,00487	8.706
Radish	40,00	4.590	25	14,60	2.680.560	0,00487	13.059
Potatoes	6,00	9.180	132	2,77	152.305	0,02415 [41]	3.678
Tomatoes	10,00	11.016	85	4,29	473.040	0,00633	2.996
Pepper	6,00*	7.344	85	4,29	189.216	0,01826	3.457
Strawberry	12,00	5.508	85	4,29	283.824	0,00692	1.965
Peas	6,00*	11.016	75	4,87	321.667	0,00730	2.351
Cabbage	19,20*	9.180	85	4,29	756.864	0,00292	2.212
Lettuce	20,00	22.032	28	13,04	5.744.057	0,00097	5.597
Spinach	20,00	5.508	30	12,17	1.340.280	0,00146	1.959
Total set-up costs							**45.980**
Margin of 20%							**9.196**
Total set-up costs with 20% margin							**55.176**

* Estimated values

Table 34 shows the estimated costs for the nutrient, fish feed and water demand of the whole Vertical Farm. A price of 2,5 €/kg is used, though values ranging from 0,5 to 5 have been found [40]. The cost sum amounts to 1.478 k€ (FY 2012) per year with 20% margin.

Table 34: Nutrient, fish feed and water consumption and cost [FY12]

Resource	Amount	Price	Total Cost [k€/a]
Nutrients (Beyond ™)	30 L/day	81,13 €/L [16]	888
Fish feed	360 kg/day	2,5 €/kg [40]	329
Water for plants	22.670 L/day	0,00185 €/L [39]	15
Total set-up costs			**1.232**
Margin of 20%			**246**
Total set-up costs with 20% margin			**1.478**

12.3.4 Personnel

The following assumptions were made to estimate the personnel costs of the VF:

- Seeding and harvesting of plants in the Vertical Farm will be done manually.
- 278 harvest events were assumed calculated by the growth period of the plants and considering 4 plant sections on every Plant Cultivation floor.
- It is estimated, based on [43], that 28 people are required to harvest the 25 Plant Cultivation Floors.
- An average salary of 50.000 €/year is assumed.

With ten crop types on 25 floors, a large number of seeding and harvesting events in the VF will occur during a year. Based on these events the amount of employees can be calculated.

The number of separate harvesting events is increased further due to the use of a staggered production cycle within the Plant Cultivation floors. The sections of the Plant Cultivation floor start, and hence finish, their plant life cycles at different times. This has the advantage of spreading out the edible biomass production over time, such that production is more continuous, but at the cost of additional labor and slightly more complexity in the design.

There are times when the harvest events for the crop species will overlap, resulting in less separate events, but increasing the work load per event. The total work load per harvest event can be expressed in terms of the total area which needs to be harvested.

Table 35: Overview of estimated required personnel for Vertical Farm operations

Task	Manual	Margin	Total
System Maintenance	5	5	10
Harvesting	20	8	28
Sowing and cleaning	2	-	2
Fish processing	3	1	4
Plant processing	3	3	6
Packaging	2	1	3
Monitoring	2	-	2
Waste management operations	1	1	2
Fish farm operations	2	1	3
Total	**40**	**20**	**60**

From [43] it is found that in the peak season, 12 skilled laborers will need to work 6 hours a day to harvest crops in a 20.000 m² greenhouse. On average, the amount of laborers during the harvest period is about 8. Assuming that the workers in the Vertical Farm work for 8 hours/day, roughly 6 people would be needed per 20.000 m² of grow area. Then, about 28 people are needed to harvest the 92.718 m² grow area of the Vertical Farm.

The total amount of labor required for the Vertical Farm is listed in Table 35. Based on the assumed average salary, yearly personnel costs of 3,6 M€ (FY 2012) with 20% margin for a total of 60 employees were estimated.

12.3.5 Cost summary recurring costs

Total recurring costs for the VF were estimated to be about 48 M€/a (FY 2012) with 20% margin (see Table 36).

Table 36: Cost summary recurring costs [FY12]

Cost Item	Total Costs [k€/a]	Margin of 20% [k€/a]	Total Costs with 20% [k€/a]
Power and Energy consumption	23.680	4.736	28.416
Equipment Replacement and Maintenance	12.101	2.421	14.522
Seeds	46	9	55
Nutrients (Beyond ™)	888	178	1.066
Fish feed	329	66	395
Water	15	3	18
Personnel	3.000	600	3.600
Total	**40.059**	**8.013**	**48.072**

12.4 Profitability

The economic feasibility of the Vertical Farm can be assessed based on the minimum required price which needs to be asked for the crops and fish produced in the farm in order to break-even. The following assumptions were made to estimate the profitability of the VF:

- Edible biomass means the sum of fish filet and crop output. This assumption was made to facilitate the overall calculation.
- An average edible biomass price per kilogram is calculated to estimate the profitability of the VF.

For the purposes of this study, it is assumed that the building costs can be amortized over a period of 30 years and that there is no rest value at the end. Similarly, for the initial equipment cost it is assumed that this can be amortized over a period of 30 years without any residual value.

The results of the calculations can be found in Table 37. It was found that the yearly costs of the Vertical Farm are over 62 M€ (FY 2012) with 20% margin.

Table 37: Vertical Farm yearly cost/revenue analysis with 20% margin [FY12]

Non-recurring cost source	**Cost [k€] with 20% margin**	**Time Period [year]**	**Total annual Cost [k€/a] with 20% margin**
Building & Equipment (initial built-up phase)	284.669	30	14.101
Recurring cost source	**Cost [k€] with 20% margin**	**Time Period [year]**	**Total annual Cost [k€/a] with 20% margin**
Power	28.416	1	28.416
Resources	1.534	1	1.534
Personnel	3.600	1	3.600
Equipment Maintenance & Replacement	14.522	1	14.522
Total annual costs with 20% margin			**62.173**

As it can be seen in Figure 47 the main cost driver of the VF baseline scenario are the power costs with 46% of the total yearly costs.

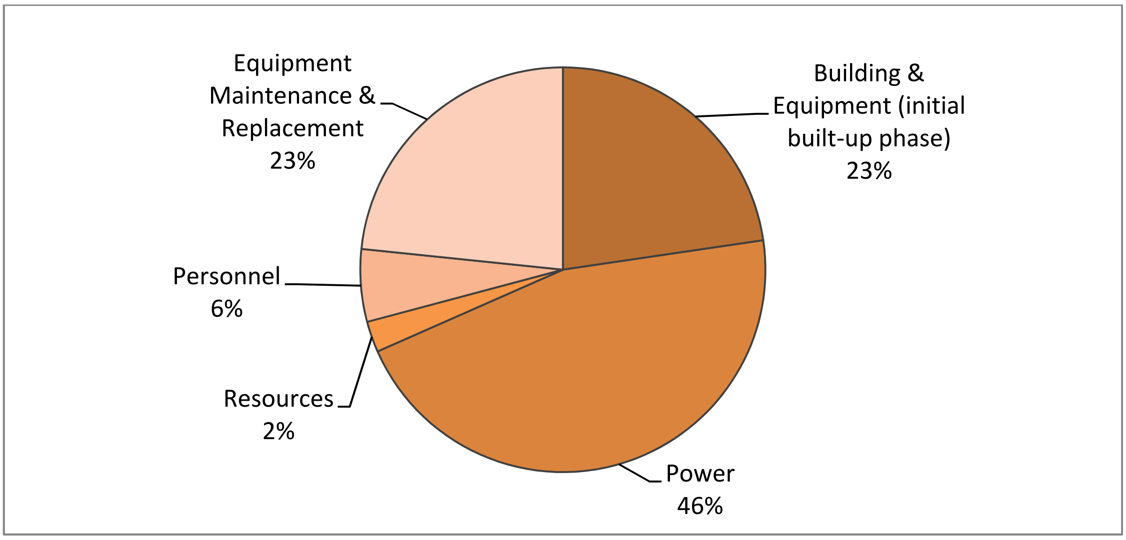


Figure 47: Cost driver for the yearly VF baseline scenario costs

For the Vertical Farm, in order to be economical feasible, it is necessary to at least cover all the expenses by generating enough revenue from the edible biomass it produces. Having calculated the total expenses and the total edible biomass production it is possible to determine the minimum average price with an amount of 12,54 € per one kg of edible biomass, which needs to be received for the VF to break-even. This can be found in Table 38.

Table 38: Calculation of minimum required price per kilogram (average) for the VF [FY12]

Parameter	Value	Unit
Total yearly costs with 20% margin	62.173	k€
Total yearly fish filet output	102	ton
Total yearly crop output	4.854	ton
Total yearly edible biomass production	4.957	ton
Required Average Edible Biomass Price (for Break-Even Operations)	**12,54**	**€/kg**

13 Alternative Scenarios

In this chapter, a few scenarios are examined to obtain an estimate of their relative performance compared to the baseline design discussed in this report.

- The first (alternative) scenario considers a Vertical Farm with 25 Plant Cultivation Floors, with waste management and water recovery, without fish farming.
- The second scenario considers a Vertical Farm with 25 Plant Cultivation Floors with water recovery, without fish farming and waste management.
- The third scenario considers a Vertical Farm with 25 Plant Cultivation Floors, without fish farming, waste management and without water recovery.

Last of all, as an indication of the merits of cultivating a specific crop in the Vertical Farm, it is analyzed what effect mono-crop production would have on the economic feasibility of the VF.

13.1 Scenario 1: No Fish Farming

The only change with respect to the baseline design is that the three floors used for fish farming are removed.

Using the same BKI building cost estimation approach like in chapter 12.2.1 it can be found that the cost for the initial building cost for the Vertical Farm with 34 floors will be 128.484 k€ (FY 2012) with a 20% margin.

Table 39: Building cost scenario 1 [FY12]

Cost Item	Total Cost [k€]
Shell of the VF	11.803
34 Floors of the VF	95.267
Total set-up costs	**107.070**
Margin of 20%	**21.414**
Total set-up costs with 20% margin	**128.484**

In addition to this, the equipment for the fish farms is no longer needed, which, as can be seen from Table 30, saves 1.573 k€ (FY 2012) with a 20% margin. As a result of that the costs for replacement and maintenance of VF equipment decrease also by 157 k€ (FY 2012) with a 20% margin.

From Table 32 it can be seen that the fish farms use 360 kWh per day of electricity, meaning that this scenario allows for reduction of the energy demand by 131.400 kWh per year. With a cost of 0,16 €/kWh, this results in savings in the amount of 25.229 € per year (FY 2012) with a 20% margin.

Without the fish farms, which ate part of the plant waste but also produced waste, the total waste being produced will decrease by about 79 kg/day. It is assumed that this change will have a negligible impact on the amount of methane gas produced or on the cost of the anaerobic digesters. Furthermore, without fish farms, there is no need to buy fish food, which allows for cost savings totaling 395 k€ per year (FY 2012) with a 20% margin.

Finally, the removal of the Fish Farming Floors also results in a smaller number of personnel needed for manual operation of the Vertical Farm. From Table 35 it can be seen that for manual operations at least 7 people will not be required if there is no fish farming. This saves 420 k€ per year (FY 2012) with a 20% margin.

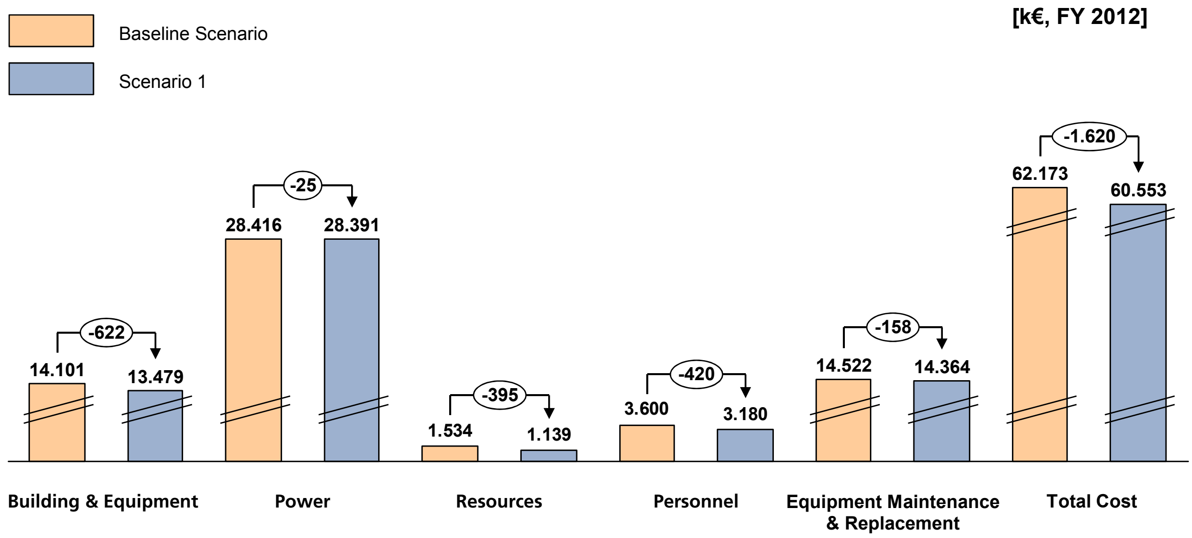


Figure 48: Cost changes from baseline scenario to scenario 1 [FY12]

As for the baseline case, the initial building costs will be divided over the 30 year lifetime, with the assumption that there is no residual value. For the initial equipment costs, it is again assumed that these need to be completely written off over a period of 30 years. The cost and revenue analysis for this scenario was carried out, using these assumptions, and the results are summarized in Table 40. The yearly costs drop to just 61 M€ (FY 2012) with a 20% margin.

Table 40: Scenario 1 cost/revenue analysis [FY12]

Non-recurring cost source	**Cost [k€] with 20% margin**	**Time Period [year]**	**Total Cost [k€/a] with 20% margin**
Building & Equipment	272.126	30	13.479
Recurring cost source	**Cost [k€] with 20% margin**	**Time Period [year]**	**Total Cost [k€/a] with 20% margin**
Power	28.391	1	28.391
Resources	1.139	1	1.139
Personnel	3.180	1	3.180
Equipment Maintenance & Replacement	14.364	1	14.364
Total yearly costs with 20% margin			**60.553**

For the Vertical Farm, in order to be economical feasible, it is necessary to at least cover all the expenses by generating enough revenue from the edible biomass it produces. Having calculated the total expenses and the total edible biomass production it is possible to determine the minimum average price with an amount of 12,48 €/kg which needs to be received for the VF to break-even. This can be found in Table 41.

Table 41: Calculation of minimum required price per kilogram (average) for scenario 1 [FY12]

Parameter	**Value**	**Unit**
Total yearly costs	60.554	k€
Total yearly crop production	4.854	ton
Required Average Edible Biomass Price (for Break-Even Operations)	12,48	€/kg

As it can be seen in Figure 49 the main cost driver of the VF scenario 1 are the power costs with 47% of the total yearly costs.

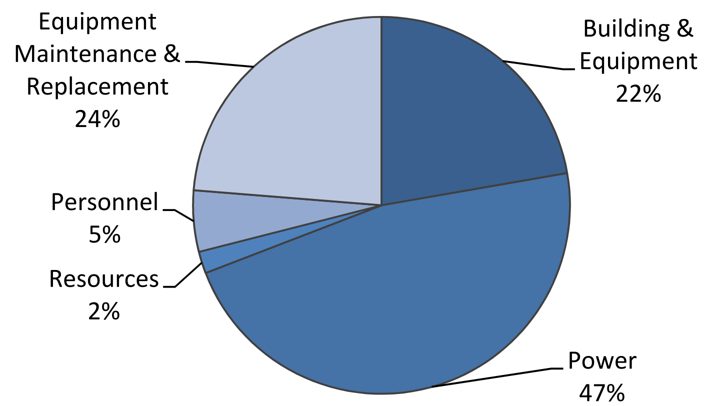


Figure 49: Cost driver for the yearly VF scenario 1 costs

Comparing this minimum price with the baseline minimum price, it can be seen that scenario 1 does not cause a significant change in average food price. Even though the building and equipment costs go down, as well as the power, equipment maintenance & replacement, resource and personnel costs, the reduction in produced fish filets of 102 t per year cancels out any cost savings.

13.2 Scenario 2: No Fish and no Waste Management

Scenario 2 changes with respect to Scenario 1 by removing the Waste Management Floors.

Using the same BKI building cost estimation approach like in chapter 12.2.1 it can be found that the cost for the initial building cost for the Vertical Farm with 32 floors will be 121.169 k€ (FY 2012) with a 20% margin.

Table 42: Building cost scenario 1 [FY12]

Cost Item	Total Cost [k€]
Shell of the VF	11.311
32 Floors of the VF	89.663
Total set-up costs	**100.974**
Margin of 20%	**20.195**
Total set-up costs with 20% margin	**121.169**

In addition to this, the equipment for the Waste Management Floor is no longer needed, which, as can be seen from Table 30, saves 8.716 k€ (FY 2012) with a 20% margin. As a result of that the costs for replacement and maintenance of VF equipment decrease also by 872 k€ (FY 2012) with a 20% margin.

From Table 32 it can be seen that the Waste Management Floors use 360 kWh per day of electricity, meaning that this scenario allows for reduction of the energy demand by 131.400 kWh per year. With a cost of 0,16 €/kWh, this results in savings in the amount of 25.229 € per year (FY 2012) with a 20% margin.

On the other hand, without Waste Management Floors, there is no methane production, meaning that the energy demand increases by 7.776 kWh/day with respect to scenario 1. This corresponds to 2.838.240 kWh per year which, at a price of 0,16 €/kWh, increases the recurring costs by 544.942 € per year (FY 2012) with 20% margin.

Additionally, because the waste is no longer processed within the Vertical Farm, it is necessary to pay an external third party to collect and process the crop waste of 9.369 kg per day. From [44] the costs of waste disposal were taken to be 20 €/ton of waste which leads to additional costs of 82.076 € per year (FY 2012) with 20% margin.

Removal of the Waste Management Floors does not lead to a reduction in resource consumption with respect to Scenario 1. It does however result in fewer people (2 persons) needing to be employed to operate the Vertical Farm. Thus, 120 k€ (FY 2012) with 20% margin is saved per year on labor costs.

As for the baseline case, the initial building and equipment costs will be divided over the 30 year lifetime, with the assumption that there is no residual value. For the initial equipment costs, it is again assumed that these need to be completely written off over a period of 30 years.

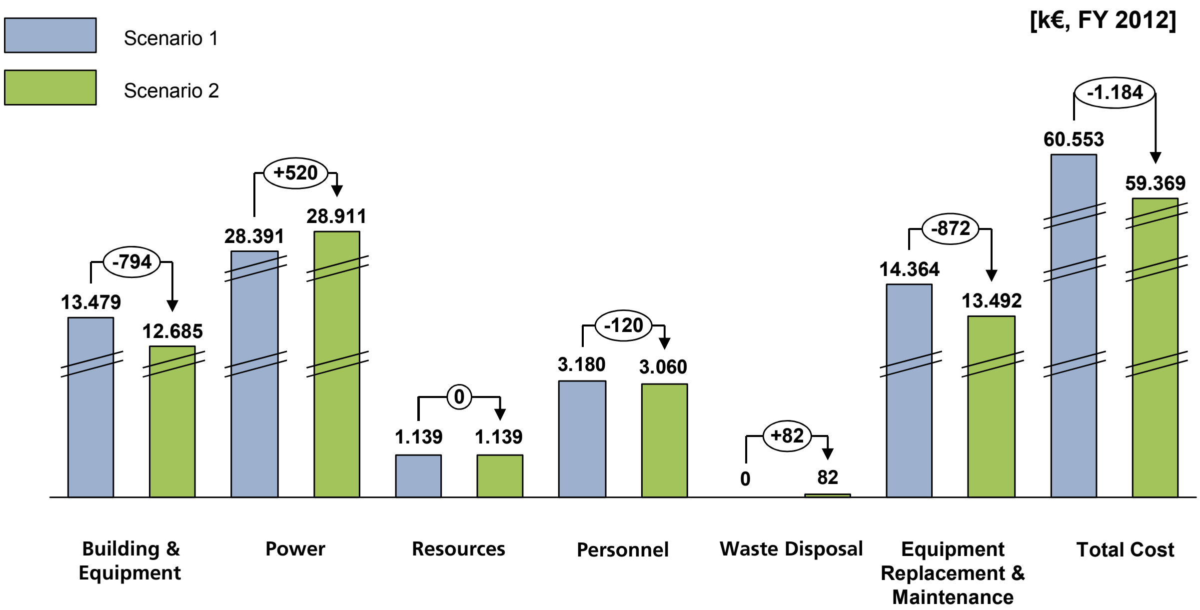


Figure 50: Cost changes from scenario 1 to scenario 2 [FY12]

The cost and revenue analysis for this scenario was carried out, using these assumptions, and the results are summarized in Table 43. The yearly costs drop to just 59M€ (FY 2012) with a 20% margin.

Table 43: Scenario 2 cost/revenue analysis [FY12]

Non-recurring cost source	**Cost [k€] with 20% margin**	**Time Period [year]**	**Total Cost [k€/a] with 20% margin**
Building & Equipment	256.095	30	12.685
Recurring cost source	**Cost [k€] with 20% margin**	**Time Period [year]**	**Total Cost [k€/a] with 20% margin**
Power	28.911	1	28.911
Resources	1.139	1	1.139
Personnel	3.060	1	3.060
Waste disposal	82	1	82
Equipment Maintenance & Replacement	13.492	1	13.492
Total yearly costs with 20% margin			**59.369**

As it can be seen in Figure 51 the main cost driver of the VF scenario 2 are the power costs with 49% of the total yearly costs. The costs for waste disposal are negligible with an amount of nearly 0%.

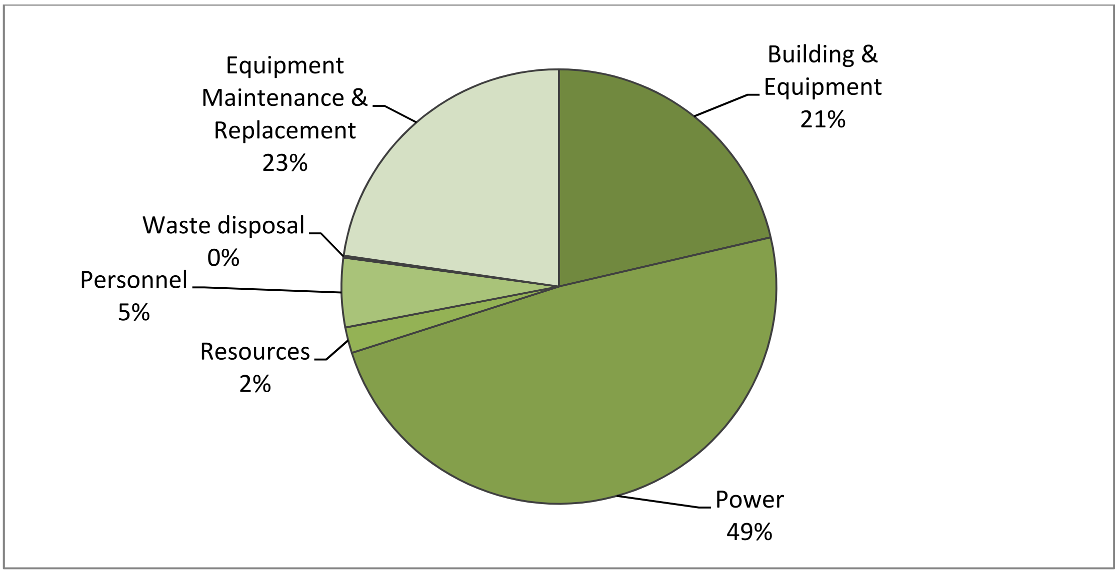


Figure 51: Cost driver for the yearly VF scenario 2 costs

For the Vertical Farm to avoid bankruptcy, it is necessary to at least cover all the expenses by generating enough revenue from the edible biomass it produces. Having calculated the total expenses and the total edible biomass production it is possible to determine the minimum average price with an amount of 12,23 €/kg which needs to be received for the VF to break-even. This can be found in Table 44.

Table 44: Calculation of minimum required price per kilogram (average) for scenario 2 [FY12]

Parameter	Value	Unit
Total yearly costs	59.369	k€
Total yearly crop production	4.854	ton
Required Average Edible Biomass Price (for Break-Even Operations)	12,23	€/kg

13.3 Scenario 3: No Fish, Waste Management and Water Recovery

Scenario 3 changes with respect to Scenario 2 by removing the water recovery process. Instead of condensing the water in the air and filtering it back for re-use, the air is simply guided out of the building and new air is brought into the building.

Since the water no longer needs to be recovered, the dehumidifier plates and associated heat exchangers are no longer required. Additionally, the water buffer tanks are no longer necessary. Furthermore, since the air is now just guided out of the building, the trace gas filters are no longer necessary. Also, the air no longer needs to be guided from the Plant Cultivation Floors to the Environmental Control Floors, allowing for savings on the ducts which need to be installed in the building, as well as the number of duct fans which are required. Finally, the heat dissipation units on the roof can be smaller, or fewer in number, because the heat from cooling the air no longer needs to be dissipated.

Using the information given in Table 22 and some estimation, it was found that the equipment cost will be reduced by 3.643 k€ (FY 2012) with 20% margin (see Table 45). For these calculations it was assumed that only half of the duct fans from the baseline design would be needed, and that the cost of the ducts is reduced by 150 k€ (FY 2012) without margin with respect to the original design. The cost of the heat dissipation units is taken to be a quarter of the costs from Table 22, since the heat which needs to be dissipated is only about a quarter of the original heat load. The dehumidifier plates, heat exchangers and water buffer tanks are no longer required. Neither is the trace gas filter, since the humid air will be rejected from the building completely.

Table 45: Cost reduction of the Environmental Floor equipment [FY12]

Equipment	Units [-]	Price [€/unit]	Total Reduction [k€]
Duct Fans	100	1.000	100
Duct system (for all Plant Cultivation Floors)	-	-	150
Dehumidifier plates	400	5.000	2.000
Heat exchangers	12	8.000	96
Water buffer tanks	12	2.500	30
Trace gas filter	12	15.000	180
Heat dissipation units	24	20.000	480
Total set-up costs			**3.036**
Margin of 20%			**607**
Total set-up costs with 20% margin			**3.643**

The power consumption of the Vertical Farm in this scenario changes compared to what was determined in Table 21 because of the significant decrease in heat load.

As mentioned above, it was assumed that only half of the duct fans from the baseline design would still be needed in this scenario. Taking the same power consumption and operating time this yields a reduction of 16.800 kWh per day. On the other hand, the Inlet / Outlet fans need to operate 24 hours per day instead of 3, resulting in an increase in daily energy consumption of 35.784 kWh. The Environmental Control Floor heat exchangers are no longer required, which saves 88.128 kWh per day. Finally, the roof heat dissipation units can be resized to handle only the 4,2 MW heat load from the LED panels, rather than the 18,9 MW of the baseline design, which allows for an energy consumption reduction of 88.320 kWh each day.

Table 46: Scenario 3 power and energy consumption modification of the Environmental Control System

Component	Units [-]	Peak power per unit [kW]	Total power [kW]	Daily Operation time [h]	Daily Energy Consumption [kWh]
Duct fan	-100	7	-700	24	-16.800
Exhaust/Inlet fan	6	284	1.704	+21	+35.784
Environmental Control Floor heat exchangers	-12	306	-3.672	24	-88.128
Roof heat dissipation units	32	-115	-3.680	24	-88.320
Total	**-**	**-**	**-6.348**	**-**	**-157.464**

Thus, per day, the power consumption is reduced by 157.464 kWh and per year 57.474 MWh can be saved, which at 0,16 €/kWh presents cost savings of 11.035 k€ per year (FY 2012) with 20% margin.

On the other hand, without water recovery, it is necessary to bring in a total of 225.410 Liters of water each day. From [39] it can be found that the price of water (in Bremen, Germany) is

1,85 €/m^3 or 0,00185 €/Liter. Using this value, the total water cost for the Vertical Farm is 183 k€ per year (FY 2012) with 20% margin.

As for the baseline case, the initial building and equipment costs will be divided over the 30 year lifetime, with the assumption that there is no residual value. For the initial equipment costs, it is again assumed that these need to be completely written off over a period of 30 years.

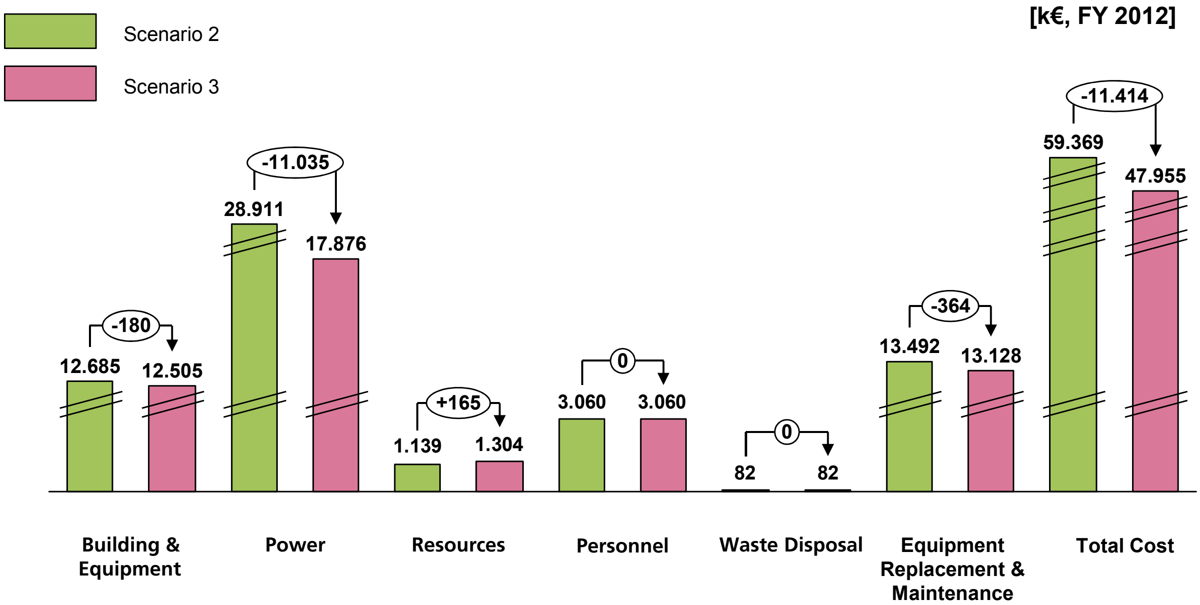


Figure 52: Cost changes from scenario 2 to scenario 3 [FY12]

The cost and revenue analysis for this scenario was carried out, using these assumptions, and the results are summarized in Figure 52. The yearly costs drop to just 48 M€ (FY 2012) with a 20% margin.

Table 47: Scenario 3 cost/revenue analysis [FY12]

Non-recurring cost source	**Cost [k€] with 20% margin**	**Time Period [year]**	**Total Cost [k€/a] with 20% margin**
Building & Equipment	252.452	30	12.505
Recurring cost source	**Cost [k€] with 20% margin**	**Time Period [year]**	**Total Cost [k€/a] with 20% margin**
Power	17.876	1	17.876
Resources	1.304	1	1.304
Personnel	3.060	1	3.060
Waste disposal	82	1	82
Equipment Maintenance & Replacement	13.128	1	13.128
Total yearly costs with 20% margin			**47.955**

As it can be seen in Figure 53 the main cost driver of the VF scenario 3 are the power costs with 37% of the total yearly costs. The costs for waste disposal are negligible with an amount of nearly 0%.

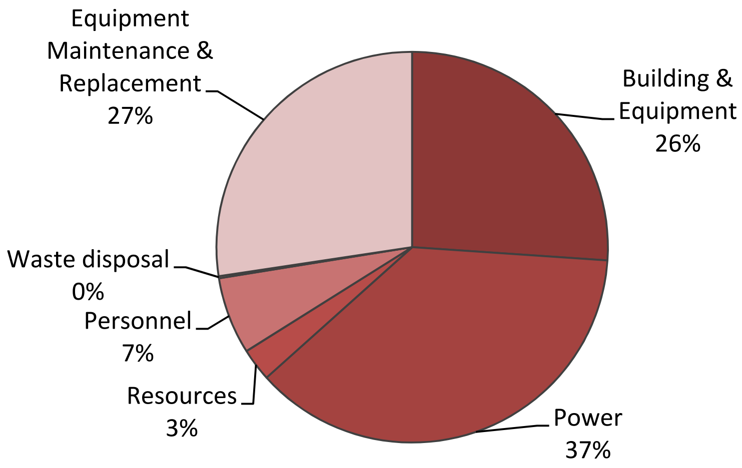


Figure 53: Cost driver for the yearly VF scenario 3 costs

For the Vertical Farm, in order to be economical feasible, it is necessary to at least cover all the expenses by generating enough revenue from the edible biomass it produces. Having calculated the total expenses and the total edible biomass production it is possible to determine the minimum average price with an amount of 9,88 €/kg which needs to be received for the VF to break-even. This can be found in Table 48.

Table 48: Calculation of minimum required price per kilogram (average) for scenario 3 [FY12]

Parameter	Value	Unit
Total yearly costs	47.955	k€
Total yearly crop production	4.854	ton
Required Average Edible Biomass Price (for Break-Even Operations)	9,88	€/kg

13.4 Mono-crop production

This section is only intended as an indication of the total output of the various crops for the case where the Vertical Farm with 25 Plant Cultivation Floors produces only a single type of crop. This can be seen in Table 49.

No minimum price has been calculated for the mono-crop scenario, because the impact on the Vertical Farm design is too large.

For example, switching from multi-crop to mono-crop production will affect the total grow area of the Vertical Farm and, hence, the total required number of LED panels. Furthermore, the lighting intensity required by the crops impacts the total power demand of the lighting system. Since part of this power demand is transformed into waste heat, the cooling system also needs to be changed.

Additionally, the water uptake and transpiration of the Plant Cultivation Floors would change, requiring significant changes to the Environmental Control Floor design. The nutrient and CO_2 uptake would also vary quite significantly from the multi-crop VF.

Changes in the total biomass yield, due to switching from multi- to mono-crop production, will furthermore impact the labour requirements as well as the waste management system, which would have to handle more (or less) bio-waste.

Table 49: Edible biomass yield for the VF crops in case of mono-crop production

Food	Total Growth Area [m²]	Edible Biomass Yield [ton/year]	Edible Biomass Yield with aeroponics [ton/year]
Lettuce	137.700	6.602	9.242
Cabbage	114.750	3.174	4.444
Spinach	137.700	3.668	5.135
Carrots	91.800	2.507	3.510
Radish	114.750	3.840	5.375
Tomatoes	91.800	5.822	8.151
Peppers	91.800	4.991	6.987
Potatoes	45.900	1.764	2.470
Peas	68.850	307	429
Strawberry	137.700	3.914	5.480

To summarize: the change from multi-crop to mono-crop production would require a substantial redesign of the Vertical Farm and as a consequence the economic analysis of the mono-crop design would differ greatly from the economic analysis of the baseline design discussed in this report and this will thus be left for possible future study.

14 Open Issues

The Vertical Farm design presented in this report is just a first phase A/ phase 0 design. There are a number of issues which need to be worked out further in any follow-up studies. These will be discussed in this chapter. Additionally, the Vertical Farm designed in this study is just one of a large number of possible designs. Some topics, which might be investigated in other studies, are also mentioned in this chapter.

14.1 Superstructure

Any Vertical Farm study will start with the building design. Several points which should be investigated in order to optimize the overall design are:

- **Number of floors**
  - In this study, a fixed number of Plant Cultivation Floors was taken for the Vertical Farm and the subsequent study only allowed for changes in the number of floors for the other systems. It is recommended that future studies determine the optimal number of Plant Cultivation Floors by determining the additional cost and production of adding more floors.
- **Building footprint**
  - The Vertical Farm discussed in this report considered a building with a square cross-section of 44 by 44 meters. Future studies should analyze the possibility of changing the cross-section shape or the dimensions and the impact on the Vertical Farm design and economic feasibility.
- **Structural design**
  - A structural analysis should be conducted on the Vertical Farm design discussed in this report to verify that it is structurally sound.
  - It was assumed that the frame of the building is comprised of a skeleton structure. Changing this material selection might allow for building cost reductions, which would improve the economic feasibility of the Vertical Farm.

14.2 Plant selection and Cultivation

There are a large number of crop combinations which can be cultivated in a Vertical Farm and each of those options will have a slightly different optimal design.

Several issues which can be investigated are:

- **Multi- or mono-crop**
  - This report focused on the design of a multi-crop Vertical Farm. Future studies may opt to focus on mono-crop production in order to try and increase the efficiency of the Vertical Farm.
- **Crop selection**
  - Depending on the crops which will be cultivated in a Vertical Farm, several design aspects may change. Floor-to-ceiling height for example will change depending on the number of plant stacks per floor and the required height per plant stack.
  - Different regions of the world may require various foods to meet the dietary needs of the people. Crop selection for the Vertical Farm should consider this.

- From an economic stand point, an analysis of seasonal high-prize crop types shall be investigated in the light of Vertical Farming (e.g. achievable market prize of strawberries during winter time in Tokyo).

- **Crop yield**
    - The data on biomass yield and resource consumption used in this report was from the NASA baseline values and assumptions document [6]. It should be investigated whether these values are for hydroponic plant cultivation with elevated levels of carbon dioxide as assumed. Additionally, the expected increase in yield due to aeroponic plant cultivation should be investigated further.
- **Grow Units, Grow Pallets and Grow Lids**
    - The system of grow lids, grow pallets and grow units described in this report for the germination and cultivation of crops should be designed in greater detail in further studies.
    - No precautions against fungi, bacteria and other unwanted organisms are taken into account in the building design. It may be necessary to consider counter-measures (e.g. airlocks) to prevent or contain diseases in the Vertical Farm.

14.3 Fish and other Animals

In case animal breeding is deemed suitable for further analysis in the context of a Vertical Farm, there are a number of issues which should be investigated:

- **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.
    - New techniques such as in-vitro meat production might be an animal friendly alternative for Vertical Farm 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 Vertical Farm. Besides the fact that the mushrooms could be sold for consumption, their protein rich waste is very applicable as Tilapia feed.
- **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.
- **Mass balance of within the aquaculture system**
    - Tilapia can be fed with plant-waste, leftover food and even feces (although regulation in some countries prohibits this). In general though the mass balance of waste disposal and nutrient production within the Vertical Farm needs to be optimized as a more detailed design becomes available.
- **Cope with 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.

- **Grow requirements for Tilapia**
    - Exact optimum grow requirements could maximize Tilapia production.
- **Genetic engineering or Crossbreeding**
    - Genetic engineering or crossbreeding provides the possibility to increase Tilapia grow rate, increase environmental resistance and Omega-3 fatty percentage.

14.4 Waste Management

Due to the low cost of waste disposal which was taken for the economic analysis of the Vertical Farm design in this report it was concluded that doing the waste management in the building would be sub-optimal.

Further investigation is warranted to verify this conclusion by analyzing the following points:

- **Waste disposal cost**
    - Changes in the cost of waste disposal by an external party could change the cost-benefit relation of handling the waste management in the Vertical Farm.
    - The possibility of selling waste (e.g. to farmers for compost) should be investigated.
- **Nutrient extraction**
    - In the current study, it was assumed that all the waste is used for biogas production. It may be more economical to use part (or all) of the waste for nutrient extraction (=> within VF's fertilizer facility)
- **Anaerobic digestion**
    - The exact reactor conditions for optimal biogas production should be determined. Additionally, the exact methane and carbon dioxide yield of the biogas should be analyzed.

14.5 Nutrient Delivery

It was assumed in this study that a commercial fertilizer could be used for the plant cultivation. Future studies should investigate some alternative aspects:

- **Nutrient solution**
    - Rather than a commercial fertilizer, customized (and optimized) nutrient solutions should be defined for the Vertical Farm crops under consideration, in order to allow for optimal crop cultivation.
    - It should be investigated whether an A/B stock system, where two different solutions are mixed with water to get the desired solution, might be more economically attractive than a precisely controlled system which manages each nutrient separately.
- **Nutrient cost**
    - Research should be done to determine the availability and bulk cost of buying the base nutrients (or A and B stocks).
    - As an alternative it should be investigated whether it might be cheaper to buy waste and extract the nutrients from this waste within the Vertical Farm.

14.6 Environmental Control

Based on the assumptions and cost estimations used in this report, it was found that using the Environmental Control Floor to recover the evapotranspiration by the plants caused a significant increase in the minimum required produce price.

With assumptions and design decisions in future studies this might be different. As such, some issues regarding the environmental control system of the Vertical Farm should be investigated more closely:

- **Building heat**
  - It was assumed that the heat transfer from the LED panels to the air was negligible. This assumption should be verified, or the design should be altered to cope with any heat transfer which does occur.
  - The heat transfer to and from the environment around the Vertical Farm has not been taken into account in this study. In reality this can have a significant effect on the environmental control design.
- **Air flow**
  - Only the air flow through the Plant Cultivation Floors has been considered in this study. Future studies should alter the design to cope with the remaining floors as well.
  - The loss of air through leakage and expulsion of trace gases has not been taken into account in this report. More detailed designs will need to address such issues.

14.7 Lighting and Power

One of the pre-study design choices for the Vertical Farm was the decision to only use artificial lighting within the building. Additionally, the only power being generated by the Vertical Farm was as a result of the methane produced through waste management. In reality it might be more economically viable to use a combination of artificial and natural lighting and to investigate other methods of power generation. As such, a list of possible future research topics has been created:

- **Natural and artificial lighting**
  - To allow natural lighting to reach deep within a building, a collection, transport and distribution system is required. Large solar collectors on top of the building, coupled with fibre optic cables or other light tubes, might be a good addition to artificial lighting. The costs of such a system would of course need to be compared with the costs of a purely artificial lighting system.
  - Several assumptions were made regarding the PPF and light spectrum produced by the LED panels. Future studies should verify these assumptions or alter the design accordingly.
- **Power generation**
  - Large wind turbines could be placed on top of the building to generate electricity. Depending on the cost of the system and the potential amount of electricity generated, this might reduce the minimum required food price.
  - Aside from the possibility of generating wind power, it should be investigated whether it is economically attractive to place solar panels on the sides of the building in order to generate electricity. Again, the cost needs to be weighed against the potential electricity generation.
  - Often, power plants offer time-depending cost reductions, if energy is used during night time (~40-60 % reduction). Since the VF is independent from the outside day/ night periods, this approach can lead to significant cost savings. This should be further analysed when power costs are estimated.

- **Power saving**
  - Light shutter strategies should be investigated in order to further decrease energy demands. These strategies foresee to put the LEDs into an on/ off mode (not recognizable by the plants).
  - Inner canopy lighting strategies shall be investigated in order to increase the overall light-to-plant factor and therefore further decrease power demands or maximize yield.
  - Not considered in the power calculation are the plant life cycle depending variable light intensity adjustments. Early plants (e.g. sprouts need less light intensity than plants that are in the vegetative state). This way the power calculation inhabits a solid margin which need to further investigated in the future in order to lower the power demand.

14.8 Cost

The cost estimations and economic analysis carried out in this report are still quite rough. Some aspects which should be investigated in more detail are listed below:

- **Initial start-up loan and interest rate**
  - Given the nature of the Vertical Farm project, and the large costs, it is likely that some government funding will be required. The specific conditions for acquiring this funding should be investigated.
- **Equipment cost, maintenance and replacement**
  - The initial equipment costs, as well as the costs of maintaining and replacing equipment make up a significant part of the Vertical Farm expenses. Further studies should improve the accuracy of the cost estimations.
- **Other cost assumptions**
  - While not as large a part of the Vertical Farm expenses as the building, equipment or power, the costs of the personnel and other resources should still be verified or adjusted based on more accurate data.
- **Personnel cost**
  - Detailed personnel planning shall be done in order to elaborate the exact size of the staff team. Analysis on necessary harvest events, seeding procedures, cleaning & disinfection protocols, post processing procedures shall be performed in the future.
- **Carbon dioxide trading**
  - The Vertical Farm has a net uptake of carbon dioxide. Given the current concern with global warming and the role of carbon dioxide within this process, as well as the regulations in place at this moment, it is likely that money can be made through carbon dioxide trading.

14.9 Other Vertical Farming concepts

During the study the team had to make consensus on one VF design layout in order to go along with the iteration steps and to elaborate the system and subsystem designs. Of course other VF designs are thinkable, which might offer new options.

- **System Analysis**
  - Future studies shall investigate other layouts for a Vertical Farm. In particular a detailed system analysis shall be undertaken to find out the various superstructure layout options. One tall building versus several small buildings

within a city block is just one question that shall be answered with proper system analysis tools.

- **Numerical Optimization**
  - Layout questions on floor level are an important topic for future studies as well. Here, the question is of how dense or compact the grow accommodation can be achieved on each Plant Cultivation Floor? To answer these questions numerical optimization algorithms could lead to an optimum. Also several new approaches within the domain of High Density Vertical Growth (HDVG) shall be investigated.
- **Inner city Interface**
  - The interactions between the Vertical Farm and the surrounding city entities within a mega city could be an area of investigation. Here, the input/ output relationships of the VF shall be investigated in more detail and how to use local unwanted substances e.g. CO_2 emission from power plants or bio waste from schools and hospitals. Huge benefits can occur when the VF is integrated within the mega city structure by adapting the closed loop paradigm (e.g. bioregenerative life support systems) of the space sector on city planning level.
  - For future studies it is advisable to integrate city planners as well as community officials in the planning process.
  - Public Engagement is of great importance and proper ways to integrate the city population into the VF endeavour shall be investigated further. Possible examples like public observation decks, integrated restaurants and educational center (possible topics: recourse efficient living, sustainability, environment, world food situation) could be elaborate in the future.

15 Conclusion

15.1 Comparison with Traditional Agriculture

Field plant cultivation (climatic influences) and in closed environment (protected cultivation) create different amounts of yield. Column four of Table 50 provides the required agricultural land in hectare to fulfil the VF plant yield, shown in column three for every plant w.r.t. the baseline scenario.

There is an increase in yield of all crops in the Vertical Farm plant cultivation. To produce an equal amount of edible output than that produced in a VF with a footprint of 1.936 m², an area of 216 ha in field is needed (see Figure 54). This is a required agricultural land increase factor of 1.115.

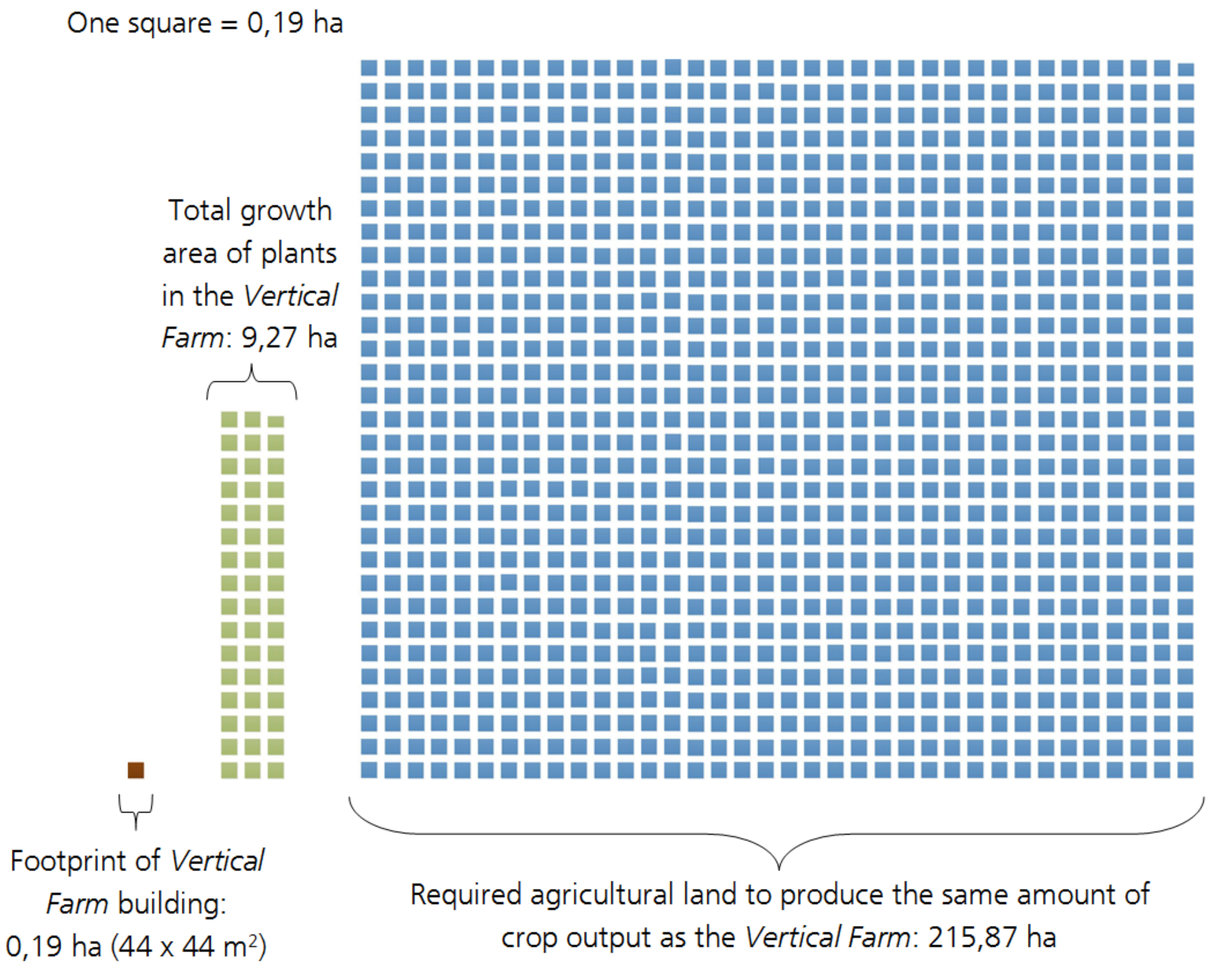


Figure 54: Vertical Farm compared to Traditional Agriculture

The increases in yield of the VF are the result of protected environment (optimized growth conditions), shortened growth periods and additional numbers of growth periods and harvests per year (no seasonal restrictions) as well as plant area expansion/ maximization (vertical stackings).

Table 50: Yield comparison of the Vertical Farm and field cultivation

Crops	Expected yield in field agriculture [tons/ha*year], [REF]		Baseline Scenario		Mono-crop Scenarios		
			Yield of VF* [tons/year]	Required agricultural land to fulfil VF output [ha]	Yield of VF* [ton/year]	Required agricultural land to fulfil VF output [ha]	Area Ratio for Equal Biomass Output
Lettuce	23	[45]	1.478,78	64,29	9.242	401,83	2.075,55
Cabbage	27	[46]	355,49	13,17	4.444	164,59	850,17
Spinach	12	[47]	205,38	17,12	5.135	427,92	2.210,31
Carrots	30	[48]	280,83	9,36	3.510	117,00	604,34
Radish	13	[49]	215,01	16,54	5.375	413,46	2.135,65
Tomatoes	37	[50]	978,12	26,44	8.151	220,30	1.137,90
Peppers	49	[51]	558,94	11,41	6.987	142,59	736,53
Potatoes	20	[52]	493,96	24,70	2.470	123,50	637,91
Peas	3	[53]	68,67	22,89	429	143,00	738,64
Strawberry	22	[54]	219,2	9,96	5.480	249,09	1.286,63
Total			**4.854,37**	**215,87**			

* include aeroponic increase factor 1,4

Table 50 also displays the mono-crop scenario (columns five to seven). The highest area ratio for the mono-crop scenarios is reached in case of spinach. To produce the VF output of 5.135 tons of spinach per year an agricultural land of 428 ha is needed. This leads to an agricultural land increase factor of 2.210 times, compared to the footprint of the VF building.

15.2 Vertical Farm Summary

A Concurrent Engineering study was carried out at the DLR in Bremen to assess the economic feasibility of the Vertical Farm idea. The feasibility was determined by calculating the minimum average price required (for the food produced in the Vertical Farm) in order to cover the costs.

The study focused on the design of a Vertical Farm with plant cultivation and fish farming. To close the production cycle, waste management and water recovery techniques were implemented. The following floor description shall highlight the main features of the Vertical Farm.

A Germination Floor is used for the initial germination of all crop seeds. The floor contains twelve controlled environment chambers (Germination Units) which can accommodate up to 10.800 seed trays (Grow Lids) and several tens of thousands of seeds at a time. Additionally, this floor comprises of machines for cleaning and sterilization of equipment. These machines are used to prevent and, when necessary, destroy contaminants, fungi and other sources of disease which might threaten food production. Finally, a laboratory is located on the Germination Floor for the analysis of samples from the whole Vertical Farm.

There are 25 Plant Cultivation Floors in the building. These floors are used for the cultivation of ten different crop species. A total edible biomass output of around 13,3 tons/day and about 4.900 tons/year can be achieved with a total grow area of ca. 93.000 m^2. Each of the Plant Cultivation Floors is divided into four different sections, and only a single crop type is grown per floor. The sections of one floor are seeded and harvested at a different time, to allow for a more distributed output of food. The plants are grown in special Grow Units, which can hold up to a maximum of six Grow Pallets, depending on the crop type. The Grow Pallets provide a support structure for the plants and house sensors to monitor the local environmental conditions.

Aside from plant germination and cultivation, three Fish Farming Floors are dedicated to the cultivation of tilapia fish. A total of ca. 2.100 tilapia fish can be produced per day, which corresponds to roughly 280 kg/day and 100 tons/year of tilapia filet. The fish are kept in circular tanks of different dimensions, according to a pre-defined stocking rate based on the size of the fish. The tanks are connected to water management systems which re-circulate the water, maintaining desired conditions and separating out waste. The tilapia fish are fed a mixture of non-edible plant biomass produced in the Vertical Farm and high-protein fish feed which is bought from an external supplier.

A total of 225.000 Liters/day of water is calculated to be required for plant cultivation, along with around 30 Liters/day of a commercial nutrient solution, Beyond ™. By cooling the air and capturing the condensed water, most of the water can be recovered, leaving a total of 23.000 Liters/day which needs to be supplied from outside the Vertical Farm. The water and nutrients are stored on one Nutrient Delivery Floor at the top of the building and are pumped down to the Plant Cultivation Floors as needed. There, the water and nutrients are mixed in the desired quantities, heated or cooled to the desired temperature and delivered to the plants.

To allow precise control over the light spectrum, intensity and duration, LED lighting is used in the Vertical Farm. A total of 100.000 panels, including spares, are needed to provide lighting for the germination and cultivation of the plants. The lighting system has a peak power demand of 6.000 kW and an energy consumption of 81.000 kWh/day. To ensure that the LEDs can operate at optimal conditions, each Plant Cultivation Floor is outfitted with two heat exchanger systems to cool the LEDs, each capable of removing 200 kW of heat out of the building. The total peak power consumption of all the heat exchangers needed for the LED system is 2.500 kW. The energy consumption of the LED heat exchangers is 60.000 kWh/day.

To maintain the desired relative humidity for plant cultivation, it is determined that an air flow rate of around 850 m^3/s is required for the Vertical Farm. A total of three Environmental Control Floors are assigned to the air management and environmental control system, and each is designed to handle an airflow of 280 m^3/s. Each Environmental Control Floor is divided into four identical sections, similar to the Plant Cultivation Floors (PCF), and is connected to eight or nine Plant Cultivation Floors (PCF) through air ducts running along the sides of the building.

The used air arrives from the Plant Cultivation Floors to the Environmental Control Floors and passes through dehumidifier plates connected to a heat exchanger system. The plates cool the air from 25 °C to about 19 °C. The resulting water condensate is captured and stored in buffer tanks, before being filtered and re-used. After leaving the dehumidifier plates, the air is re-heated to 25 °C and forced through a filtration system which separates out any unwanted particles and trace gases. Afterwards, the dry, filtered, air is forced down to the Plant Cultivation Floors through a large air channel running down the center of the building. Large exhaust/inlet fans at the sides of the Environmental Control Floors are used to let air in or out of the building when necessary. The heat load from the LEDs and the air dehumidification is transferred to the roof through pipes filled with cooling fluid. On the roof 32 heat dissipation units ensure that the heat is rejected from the building. Cooling and re-heating of the air in the Vertical Farm requires a peak power of around 8.500 kW for the operation of the heat exchangers on the Environmental Control Floors and the heat dissipation units on the roof of the building and the energy consumption is 202.000 kWh/day. Furthermore, the fans required for the inlet and exhaust of air and the circulation of air through the building, have a peak power demand of 4.300 kW and an energy consumption of 68.000 kWh/day.

Once the fish and crops have matured and have been harvested, it is necessary to process them for shipment to supermarkets and restaurants. For this purpose, one Food Processing Floor in the Vertical Farm has been assigned to cleaning and packaging of the produced biomass. On this floor, the inedible biomass is separated from the edible biomass and thrown down a waste chute to be processed by the waste management floors. The packaged food is delivered to the ground floor, which acts as delivery and pick-up area and contains space which can be rented out as a supermarket. The excess space on this floor, which was not needed for cleaning or packaging machines, was turned into office space and a break room. Furthermore, the control room from which the entire building can be monitored is also located on this floor.

The inedible biomass ends up in a large storage container on the upper Waste Management Floor. There are two Waste Management Floors in the Vertical Farm which are designed to process the waste produced by plant and fish cultivation. The top Waste Management Floor houses five biogas domes which utilize anaerobic micro-organisms and bacteria to digest waste and produce biogas. Furthermore, this floor contains a fertilizer facility which utilizes special fermentation tubes filled with lava rock particles in order to produce/ extract nutrients from waste. The extracted nutrients, as well as some water, are then stored in tanks before being used for plant cultivation purposes. The second Waste Management Floor contains another five domes for biogas production. Furthermore, there is a gas separation system which is used to split the biogas into its major components, methane and carbon dioxide, and to remove the unwanted minor components. The methane and carbon dioxide are stored in high-pressure tanks, until needed. The methane is used to run the power generating turbines, while the carbon dioxide is injected in the Plant Cultivation Floors to increase the plant biomass yields. On average the Waste Management Floors process 9,5 tons/day of plant and fish waste. This waste can be used to produce up to 3.300 m^3/day of biogas, which corresponds to 2.000 m^3 of methane gas and 1.000 m^3 of carbon dioxide. The methane gas is used to produce up to 7.800 kWh/day of electricity, while the carbon dioxide is used to cover part of the carbon dioxide demand of 1.300 m^3/day. Even with the waste management, the Vertical Farm will therefore require a total of 300 m^3/day (by the PCFs) of carbon dioxide from external sources.

Based on a building construction database with cost data, the expected cost of the Vertical Farm building is calculated to be 140 M€ (FY 2012). Then, using best engineering estimate approaches, the cost for the equipment required for the Vertical Farm is estimated to be 145 M€ (FY 2012). A 20% margin is added to account for the inaccuracies inherent in these cost estimations. The total non-recurring cost is then calculated to be 285 M€ (FY 2012). This non-recurring cost is amortized over a period of 30 years, resulting in annuity costs of 14 M€/a (FY 2012).

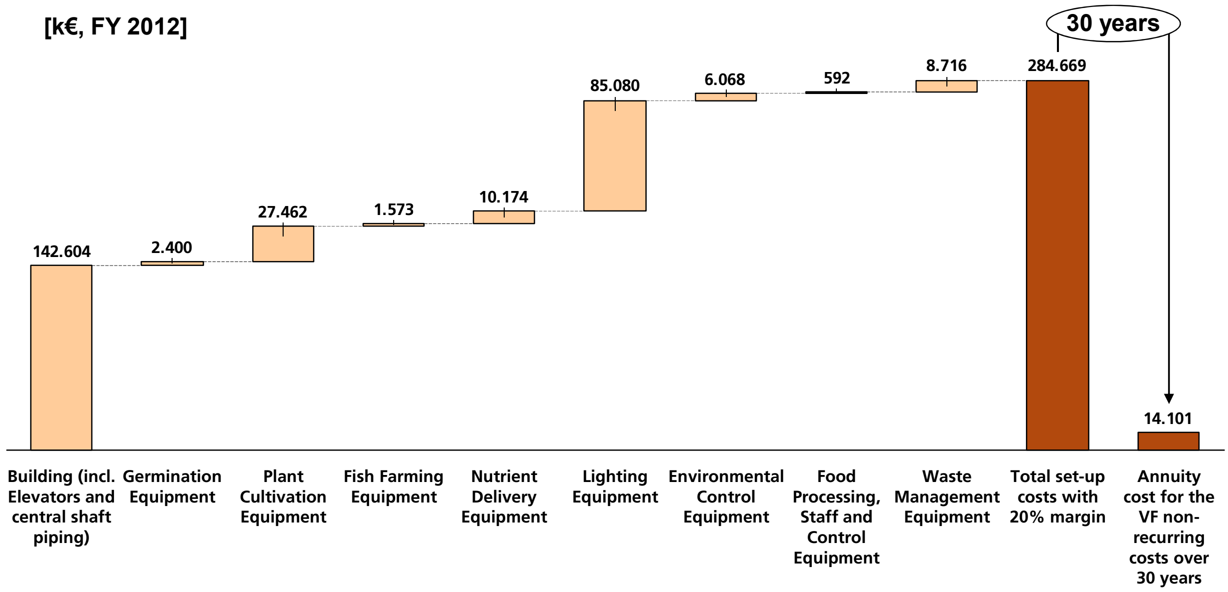


Figure 55: Annuity cost for the whole VF non-recurring costs [FY12]

Calculations and best engineering estimates are made for the power demands of the different subsystems of the Vertical Farm. It is found that the peak power consumption is around 21.300 kW and the energy consumption is roughly 405.500 kWh/day. Consequently, the energy cost is calculated to be 28.500 k€ (FY 2012) per year including a margin of 20%.

Each year 10% of the initial equipment cost is written-off to cover the costs of equipment maintenance and replacement. This amounts to 14,5 M€ (FY 2012) per year including a margin of 20%. The recurring cost of seeds, fish feed, nutrient solution and water is 1.500 k€ (FY 2012) including a margin of 20%. Personnel costs are calculated to be 3,60 M€ (FY 2012) including a margin of 20%, based on 60 employees with an average salary of 50.000 €/year. The total recurring cost is calculated to be 48 M€ (FY 2012) per year.

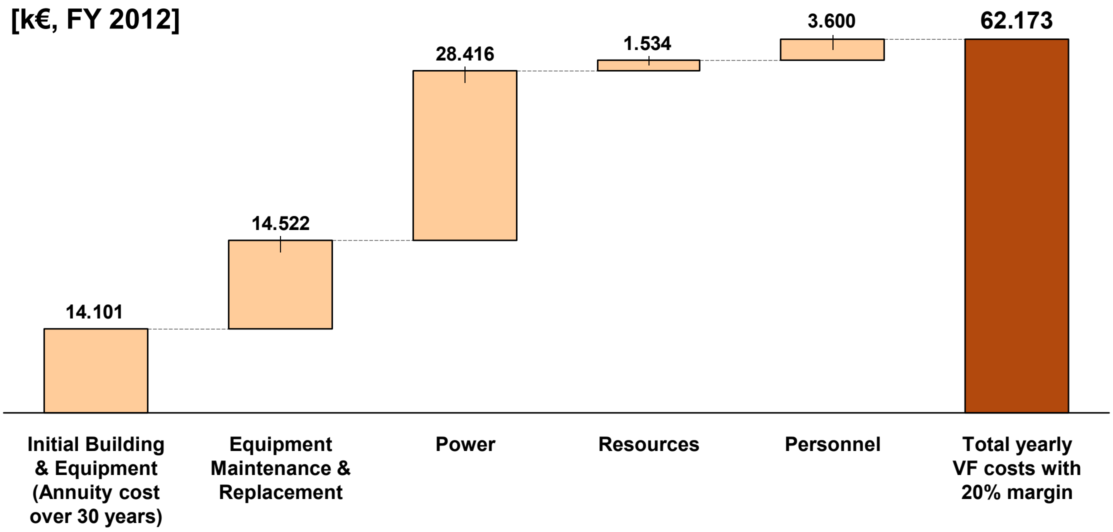


Figure 56: Cost summary VF [FY12]

The combined annual costs for the Vertical Farm, including write-offs, recurring and non-recurring costs and cost margins is calculated to be roughly 62 M€/ Year (FY 2012) including a margin of 20%. A cost distribution can be seen in Figure 56. To cover these expenses, an average food price of 12,54 €/kg is required.

Three different scenarios are examined to determine the most promising Vertical Farm design for future studies. Taking into account the changes to the Vertical Farm which occur when the Fish Farming Floors are removed from the building, the average cost per kilogram of produced food changes to 12,48 €/kg. Removing the Fish Farming Floors and the Waste Management Floors from the Vertical Farm, reduces the average cost per kilogram of produced food to 12,23 €/kg. In the last scenario, the Fish Farming Floors and Waste Management Floors are removed and no water recovery is performed on the Environmental Control Floors. As a result of these changes, the average cost per kilogram of produced food in this scenario drops to 9,88 €/kg.

Table 51: Summary of the Vertical Farm study results: Baseline Scenario [FY12]

Building Dimension	
Amount of floors	37
Plot area	50 x 50 [m²]
Food print of building	44 x 44 [m²]
Building height	167,5 [m]
Floor-to-floor height	4,5 [m] (5th basement: 5,5 [m])
Excavation	44 x 44 x 23,5 [m³]

Total growth area	92.718 [m^2]
Amount of floors	
Germination Floor	1
Plant Cultivation Floor	25
Fish Farming Floor	3
Nutrient Delivery System Floor	1
Environmental Control Floor	3
Food Processing Floor	1
Waste Management Floor	2
Basement (Supermarket Floor)	1
Waste	**Output per year [ton/year]**
Non-edible fish output and fish floor waste	394
Fresh inedible biomass yield with aeroponics	3.420
Food	**Edible Biomass Yield with aeroponics [ton/year]**
Lettuce (4 floors)	1.479
Cabbage (2 floors)	356
Spinach (1 floor)	205
Carrots (2 floors)	281
Radish (1 floor)	215
Tomatoes (3 floors)	978
Peppers (2 floors)	559
Potatoes (5 floors)	494
Peas (4 floors)	69
Strawberry (1 floor)	219
Total Plant Biomass Yield per VF	**4.854**
Tilapia Filet	**102**
Total Food Yield per VF	**4.957**
By-products	**Production per year [m^3]**
Methane	717.444
Carbon dioxide	358.722
Resource	**Consumption per year**
Electricity	148.001.295 [kWh]
Carbon dioxide	463.550 [m^3]
High-protein fish feed	131 [t]
Beyond ™ fertilizer	10.859 [L]
Personnel	60 [people]
Water	8.274.550 [L]
Cost source with 20% margin	**Cost per year [k€]**
Initial Building & Equipment*	14.101
Equipment Maintenance and Replacement**	14.522
Power	28.416
Seeds	55
Nutrients (Beyond ™)	1.066
Fish feed	395
Water	18
Personnel	3.600
Total costs per year with 20% margin	**62.173**
Minimum required average food price	**12,54 €/kg**

* Initial building and equipment costs are amortized over 30 years, with no residual value. An interest rate of 3,0% is assumed.
** Assumed to be 10% of initial equipment costs per year.

Finally, the consequences of some of the pre-CE study design decisions were examined. Three scenarios were compared to the baseline design to determine the impact of fish farming, waste management and water recovery on the economic feasibility of the Vertical Farm.

In Scenario 1, fish farming was removed from the Vertical Farm, leading to a pure crop production VF. Scenario 2 considered a Vertical Farm without fish farming and waste management. Scenario 3 analysed a Vertical Farm without fish farming, waste management and water recovery. Table 52 presents the required minimum prices for the food produced in the Vertical Farm in order to cover all expenses.

Table 52: VF scenarios and the corresponding minimum (average) food prices [FY12]

Scenario	Minimum price [€/kg]
Baseline Vertical Farm	12,54
Scenario 1	12,48
Scenario 2	12,23
Scenario 3	9,88

While the estimations and assumptions were quite rough at times, some conclusions can nonetheless be drawn from the comparison of these scenarios with the baseline design. The low cost of 20 €/ton which was assumed for waste disposal makes it cheaper to forego waste management in the Vertical Farm.

The high costs of cooling air to recover the water in the Vertical Farm are significantly higher than the costs of bringing in water from the outside, meaning that water recovery should not be pursued for future design studies.

Based on these scenarios and the corresponding minimum food prices, it is concluded that water recovery and waste management are not cost effective in areas with low water prices and low waste removal costs and should not be investigated in further design studies.

15.3 Statement

Concluding the study, one can say, at present time, the prize for producing one kg of biomass in the envisioned Vertical Farm is considerable too high. This finding is independent from the scenario that was chosen (baseline scenario of 12,54 € to scenario 3 of 9,88 € per kg).
Nevertheless, major margins are built in within yield calculation, energy consumption and cost analysis. The following aspects will further enable the general economic feasibility of the Vertical Farm:

- **Shorter grow phases:** Margins are built in with respect to the general plant life cycle and so the production cycles. The grow parameters from [6] include the germination process (ca. 1-2 weeks) as well. As these phases are executed within the separate floor (Germination Floor), the overall productions cycle is in reality shorter than as calculated in this report. This way overall biomass output will be higher which results in lower price per kg.

- **Innovative cultivation recipes:** Latest research evidence suggest that through PAR-specific lighting strategies or so called 'light recipes', including inner canopy lighting systems and maximized day/night illumination schedules, the yield limitations can further be pushed. Also new plant varieties, specially bred for an implementation within a Vertical Farm, can have positive impacts to the yield maximization. Further research in this field can therefore push the biomass output and thus decrease the price.

- **Energy savings:** Energy costs represent a major portion of the overall recurring costs. The price of one kWh was set to 0,16 € which already reflects the future price development. Present energy prices for energy intensive production industry are lower and could contribute further to cost saving. Power plants also offer time-depending cost reductions, if energy is used during night time (~40-60 % reduction). Since the VF is independent from the outside day/ night periods, this approach can lead to significant cost savings. Also the implementation of regenerative energy conversion systems like wind turbines on the roof and solar cell as general wall panelling will contribute to a more balanced power budget. Although, still in the early development phase, LED shutter strategies (LEDs in high frequency on/off mode) will lower the duty cycle. Furthermore, the light intensity adjustments, according to the life cycle state of the plants was not considered, which inhabits additional energy savings. Last but not least, the LED cooling system was designed to handle a worst case scenario (highest grow area per PCF & highest PPF demand). This way, quite a conservative calculation was done, which reflects a big additional margin. Adding up all mentioned energy saving potentials will decrease the total Vertical Farm energy demand and thus reduce the price per kg of biomass.

- **VF Design adjustments:** Further cost savings can be achieved by designing a Vertical Farm in a different manner. As stated earlier the present VF concept was designed under a *show case* agenda, meaning that several functions and floors are not necessary when following a more strict cost saving imperative. Also general cost savings can be achieved by optimizing the overall design of the Vertical Farm (e.g. instead of one tall building with 37 floors it might be cheaper to design a whole city block with 5 building that are less higher (e.g. only 10 floors each). This could result in less complexity and so less cost.

- **Cost analysis:** Several cost items were estimated with high margins and significant savings can be made during future studies. To mention one example, the maintenance cost (10% of the initial equipment cost) account to an annual cost item of ca. 14 M€. This factor might be reduced by half or even more.

Considering the above listed aspects, it is the opinion of the CE-study team and the DLR E.D.E.N. research team that the achievable price for a break-even production within a Vertical Farm can be reduced to 3-5 € per kg of biomass. A necessity of this, are financial contributions within this research domain over the next years. Of course a break-even price of 3-5 € is still above the present vegetable and food prices. Nevertheless, one has to consider that this price would be…

- …independent from grow seasons (so e.g. same price for strawberries in summer as during winter),

- …independent from e.g. unpredictable droughts, floods or insects plagues,

- …and independent from the location, which means the Vertical Farm could produce fresh crops any place in the world.

Especially, the last point is interesting for three regions on our planet, where traditional agriculture is not or only to some extent feasible. The first group are the desert countries, like for example Saudi-Arabia and Dubai. These countries are trying to gain food independency for their population, while being located in extreme arid regions with almost no fertile land.

Second potential group can be seen within Taiga states, like for example Siberia, Canada, Sweden and Iceland. Agriculture limitation factors are seasonal restrictions with only a short summer and a long winter.

Last group can be seen within mega cities, where no agriculture land is present at all, but a huge number of consumers are living in. Here, Vertical Farms can provide in-situ fresh food for the population. The target mega cities should be seen within high-income industrial areas like Northern America, Europe and Asia.

The calculated Vertical Farm (baseline scenario) produces on a footprint area of 1.936 m² the same amount of fresh crops as 216 ha of traditional field agriculture (or horticulture). This is an increase factor of 1.115. For mono crop scenario calculations, this value (in case of Spinach) rises even to 428 ha of equal agriculture land (increase factor of 2.210).

Investing in the Controlled Environment Agriculture (CEA) research domain can further push the Technology Readiness Level (TRL) of key Vertical Farming technologies. This will open-up the door to a new market idea and will strengthen the international community in facing the global food situation in the coming 50 years.

16 Acknowledgement

The present study was performed by the study group seen in Figure 57. The German Aerospace Center (DLR) wants to thank the DLR employees as well as the students for their involvement in this preliminary design study.

Special thanks to Conrad Zeidler and Vincent Vrakking for editing and adjusting essential chapter parts of this report.

Figure 57: Vertical Farm Concurrent Engineering study team

From right to left:

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Vincent Vrakking	University of Delft (Aerospace Engineering)
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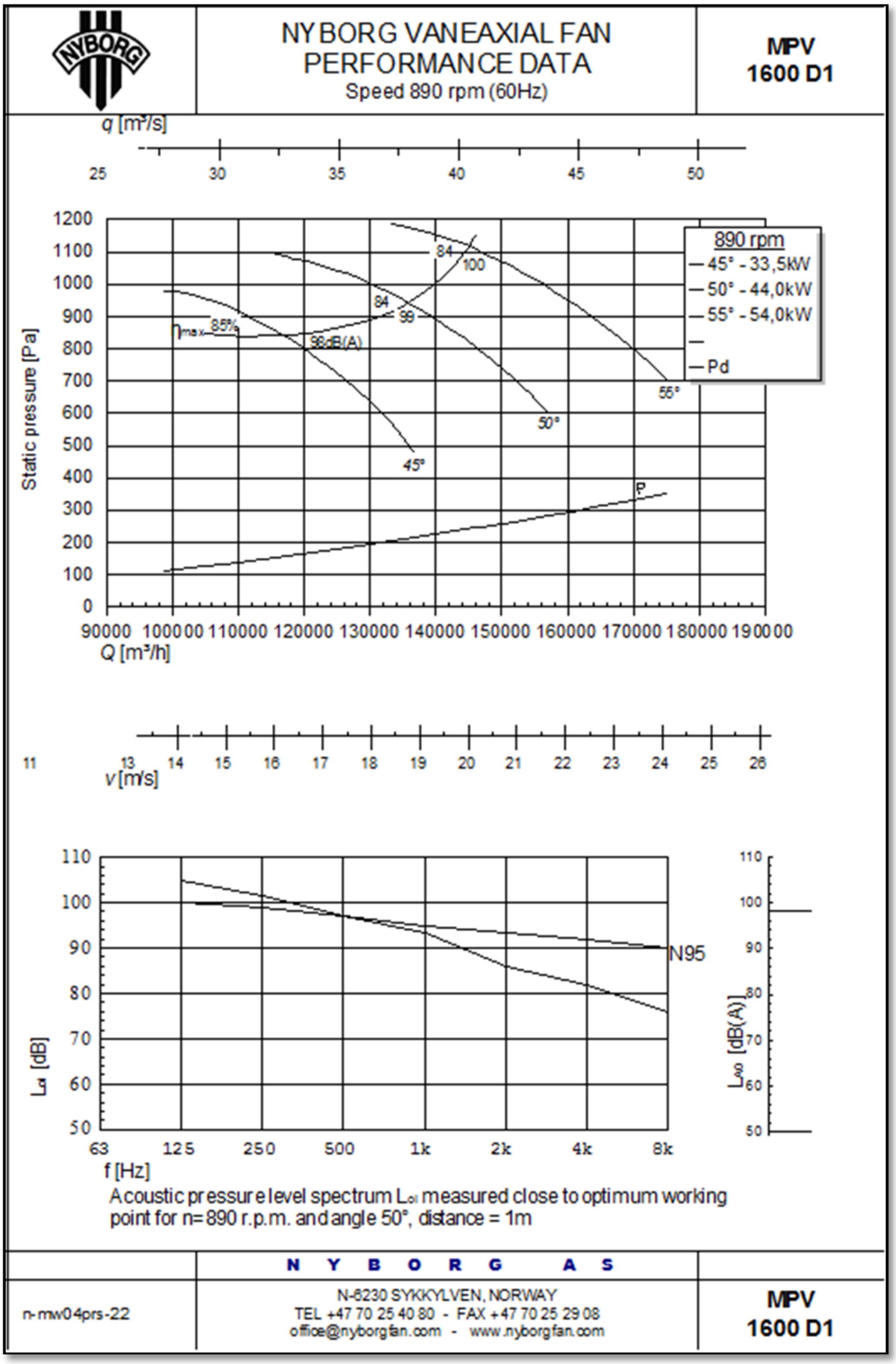
References

[1] "Greenhouse Module for Space System: proposal to ESA", 2012, DLR Bremen
[2] "NASA Systems Engineering Handbook", 1995, http://snebulos.mit.edu/projects/reference/NASA-Generic/NASA-STD-8739-8.pdf
[3] "Space Efficiency in High-rise office buildings", http://jfa.arch.metu.edu.tr/archive/0258-5316/2009/cilt26/sayi_2/69-89.pdf
[4] "Fundamentals of tall buildings", http://www.halvorsonandpartners.com/explore/53
[5] "Accessibility design manual", http://www.un.org/esa/socdev/enable/designm/AD2-04.htm
[6] "Advanced Life Support Baseline Values and Assumptions Document", 2004, A. J. Hanford, NASA
[7] "Candidate Crop Evaluation For Advanced Life Support", R.M. Wheeler, N.C. Yorio, G.D. Goins, G.W. Stutte, N.A. Cranston and L.M. Ruffe, http://www.dsls.usra.edu/meetings/bio2001/pdf/033.pdf
[8] "Comparison of hydroponic and aeroponic cultivation systems for the production of potato minitubers", 2001, E. Ritter, B. Angulo, P. Riga, C. Herrán, J. Relloso and M. San Jose, http://www.springerlink.com/content/q21136170183051l/
[9] *National Aeronautics and Space Administration NASA*, Publication and graphics department NASA Center of AeroSpace Information CASI: "*2006 Spinoff*" (2007, USA). spinoff.nasa.gov/
[10] "Tank Culture of Tilapia", 1989, J.E. Rakocy, http://aqua.ucdavis.edu/DatabaseRoot/pdf/282FS.pdf
[11] "Tank Culture of Tilapia (revision)", 2009, D.P. DeLong, T.M. Losordo, J.E. Rakocy, https://srac.tamu.edu/index.cfm/event/getFactSheet/whichfactsheet/52/
[12] "Use of some plant wastes for fish feeding with reference on its impact", 2012, M. Metwally, A. Elgellal, http://www.ipcbee.com/vol34/017-ICBET2012-B1003.pdf
[13] "International Standards for Responsible Tilapia Aquaculture", 2009, World Wildlife Fund, http://www.worldwildlife.org/what/globalmarkets/aquaculture/WWFBinaryitem14693.pdf
[14] "Vorschriften vor Nicht für den menschlichen Verzehr bestimmte tierische Nebenprodukte", 2008, http://europa.eu/legislation_summaries/food_safety/animal_nutrition/f81001_de.htm
[15] Aquaponics Library: *"The aeroponic system"*. Available from aquaponicslibrary.20megsfree.com/aeroponi.htm
[16] *AgriHouse, Inc.* Biocontroler.com, Eco-friendly Biopesticides: *"Aeroponic products"*. Available from http://www.biocontrols.com/secure/shop/item.aspx?itemid=17
[17] "*Bloom*Power black", http://www.spled.de/main_black.html
[18] "Wall Mounted Systems", http://www.fujitsugeneral.com/wallmountedRLS2_specs.htm
[19] "How high will SEER go?", http://www.achrnews.com/articles/how-high-will-seer-go
[20] "Thermal Management of high-power LEDs", http://en.wikipedia.org/wiki/Thermal_management_of_high-power_LEDs
[21] "Seasonal Energy Efficiency Ratio", http://en.wikipedia.org/wiki/Energy_efficiency_ratio
[22] "AMCA International inmotion – spring 2010", http://www.amca.org/UserFiles/file/AMCA_Spring2010Rev(1).pdf
[23] "Air conditioning Psychrometrics", http://www.cedengineering.com/upload/Air%20Conditioning%20Psychrometrics.pdf
[24] "Psychrometric chart calculator", http://mackellar.com.au/mi-ashare-phycomatric-chart.html
[25] "Axial Fans & Vane-axial Fans", http://www.nyborgfan.com/userfiles/Site_1/file/02%20Axial%20Flow%20Fans.pdf
[26] "Anaerobic Digestion of Organic Solid Wastes: An Overview of Research Achievements and Perspectives", 2000, J. Mata-Alvarez, S. Mace
[27] "High Solids Anaerobic Digestion for Energy and Nutrient Recovery", 2010, Timothy Ewing, Washington University, http://www.pacificbiomass.org/documents/Ewing%20(C2).pdf
[28] "Energy production from agricultural residues: High methane yields in pilot-scale two-stage anaerobic digestion", 2007, W. Parawiraa, J.S. Read, B. Mattiasson, L. Björnsson

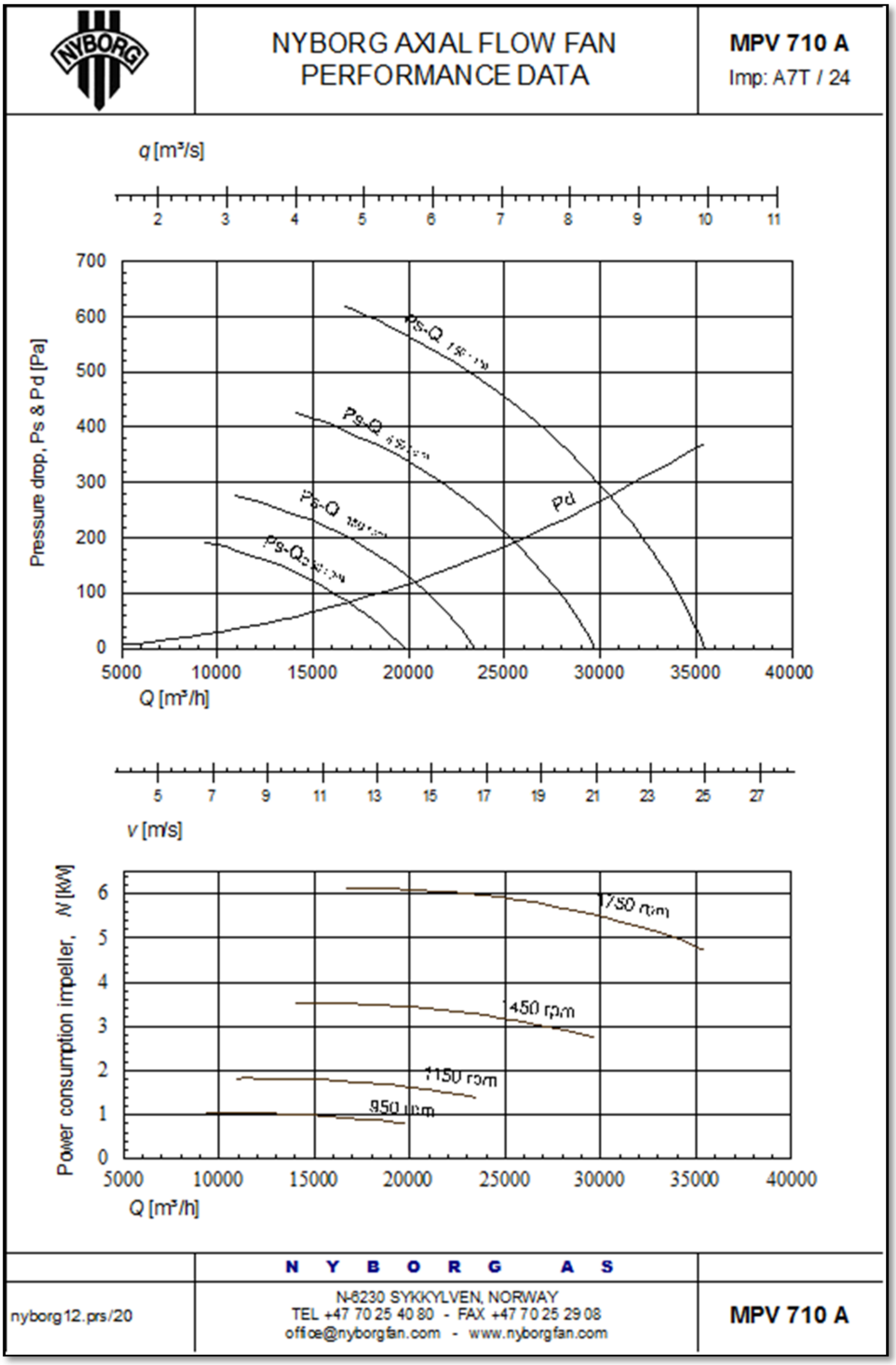
[29] "A rough guide to Anaerobic Digestion Costs and MSW diversion", http://infohouse.p2ric.org/ref/44/43217.pdf
[30] "Effect of Different Organic Loading Rate on Biological Pretreatment to Chemical Pulping Process", 2006, K.M.B.K. Ishak, http://umpir.ump.edu.my/575/1/Ku_Marsilla_Ku_Ishak.pdf
[31] "Renewable Energy from crops and agrowastes", http://www.cropgen.soton.ac.uk/deliverables.htm
[32] "Effect of organic loading rates (OLR) on production of methane from anaerobic digestion of vegetables waste", 2011, A. Babaee and J. Shayegan, http://www.ep.liu.se/ecp/057/vol1/055/ecp57vol1_055.pdf
[33] "Biogas as a potential renewable energy source: A Ghanaian case study", 2010, R. Arthur, M. F. Baidoo, E. Antwi
[34] BKI Baukosteninformationszentrum, BKI Baukosten Gebäude 2010: Statistische Kostenkennwerte Teil 1, Stuttgart: BKI, 2010.
[35] "Grundstückspreise Berlin" http://www.immowelt.de/immobilien/immomarktkauf.aspx?geoid=108110&etype=3&esr=1
[36] "Annuitätenmethode", http://de.wikipedia.org/wiki/Annuit%C3%A4tenmethode
[37] Interview with Till Brockmann of SWB-Group; Bremen; 20.07.2012
[38] "Methane", http://fr.wikipedia.org/wiki/Methane
[39] "swb Wasser basis", http://www.swb-gruppe.de/geschaeftskunden/bremen/produkte/swb-wasser-basis.php
[40] „Manufacturers, Suppliers, Exporters & Importers from the world's largest online B2B marketplace-Alibaba", www.alibaba.com
[41] „Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V.", http://www.ktbl.de/
[42] "Crop Production for Advanced Life Support Systems – Observations from the Kennedy Space Center Breadboard Project", 2003, R.M. Wheeler et al.
[43] "An Autonomous Robot for Harvesting Cucumbers in Greenhouses", 2002, E.J. van Henten et al., http://glorfindel.mavrinac.com/~aaron/school/pdf/vanhenten02_cukes.pdf
[44] "Economic analysis of anaerobic digestion- A case of Green power biogas plant in the Netherlands", 2009, S.A. Gebrezgabher, M.P.M. Meuwissen, A.G.J.M. Oude Lansink, B.A.M. Prins, http://www.ifmaonline.org/pdf/congress/09_Gebrezgabher_etal.pdf
[45] "Growth and Yield of Lettuce (Lactuca sativa L.) At Abakaliki Agro-Ecological Zone of Southeastern Nigeria", 2010, E.N.Ogbodo, P.O.Okorie and E.B. Utobo, http://www.idosi.org/wjas/wjas6%282%29/5.pdf
[46] "Cabbage Production", Douglas C. Sanders, http://www.ces.ncsu.edu/depts/hort/hil/hil-7.html
[47] "Spinach", Douglas C. Sanders, http://www.ces.ncsu.edu/depts/hort/hil/hil-17.html
[48] "Commercial Carrot Production", Douglas C. Sanders, http://www.ces.ncsu.edu/depts/hort/hil/hil-9.html
[49] "Radish - VEGETABLE CROPS PRODUCTION GUIDE FOR THE ATLANTIC PROVINCES", http://www.nr.gov.nl.ca/nr/agrifoods/crops/veg_pdfs/radish.pdf
[50] "FRESH MARKET TOMATO PRODUCTION", Douglas C. Sanders, http://www.ces.ncsu.edu/depts/hort/hil/pdf/hil-28-a.pdf
[51] "Peppers, Commercial Vegetable Production Guides, North Willamette Research and Extension Center", http://nwrec.hort.oregonstate.edu/pepper.html
[52] "Potato Health Management", http://www.ces.ncsu.edu/plymouth/pubs/potatoHealth.html
[53] "Peas - Field Pea Yield Estimates", http://www.ag.ndsu.edu/procrop/pea/peyies07.htm
[54] "Strawberry Production" National Agricultural Statistics Service, USDA., http://www.nal.usda.gov/pgdic/Strawberry/ers/tab4.html

Appendix A

A.1 NYBORG MPV-D1 1600 VANEAXIAL FAN PERFORMANCE DIAGRAM



A.2 NYBORG MPV-A 710 AXIAL FAN PERFORMANCE DIAGRAM



Appendix B

B.1 BKI Building Cost Reference Tables

Table 53: Cost Parameters of Level 1 breakdown [32] (building type: industrial production building, mainly skeleton structure)

KG	Cost groups to the 1st level	Unit	min	€/Unit	max	min	% of 300+400	max
100	Site	m^2 FBG						
200	Opening up	m^2 FBG	5	**10**	16	1,6	**2,6**	5,1
300	Building - Construction	m^2 BGF	522	**678**	1.039	63,0	**74,0**	83,8
400	Building – Technical plants	m^2 BGF	140	**240**	443	16,2	**26,0**	37,0
	Building (300+400)	m^2 BGF	702	**918**	1.297		**100,0**	
500	Outdoor Facility	m^2 AUF	33	**54**	133	7,3	**9,4**	15,9
600	Building infrastructure equipment	m^2 BGF	-	**-**	-	-	**-**	-
700	Additional building costs	m^2 BGF	37	**123**	211	0,2	**12,8**	17,6

Table 54: Cost Parameters of Level 2 breakdown [32] (building type: industrial production building, mainly skeleton structure)

KG	Cost groups to the 2nd level	Unit	min	€/Unit	max	min	% of 300	max
310	Excavation	m^3 BGI	11	**22**	34	1,0	**3,5**	7,6
320	Foundation	m^2 GRF	154	**217**	326	16,9	**23,8**	28,7
330	Outer walls	m^2 AWF	224	**258**	301	18,3	**21,7**	26,4
340	Inner walls	m^2 IWF	142	**214**	295	9,1	**12,7**	16,0
350	Ceiling	m^2 DEF	215	**281**	372	4,3	**11,3**	22,6
360	Roof	m^2 DAF	147	**192**	255	13,0	**23,7**	31,2
370	Constructional installations	m^2 BGF	0	**13**	25	0,0	**0,5**	3,6
390	Construction area	m^2 BGF	6	**14**	28	1,4	**2,7**	6,6
							% of 400	
410	Sewage, water, gas plants	m^2 BGF	20	**25**	33	7,8	**13,2**	18,2
420	Heat-supply systems	m^2 BGF	22	**33**	49	8,7	**17,2**	23,8
430	Air conditioning systems	m^2 BGF	6	**15**	30	0,4	**4,5**	9,5
440	High voltage plants	m^2 BGF	41	**63**	108	19,4	**30,8**	45,8
450	Com. and info. technology equip.	m^2 BGF	2	**6**	13	0,8	**2,9**	6,0
460	Conveyor systems	m^2 BGF	18	**42**	127	2,4	**14,6**	37,2
470	Plants for specific usage	m^2 BGF	18	**75**	297	3,2	**16,5**	52,7
480	Building automation	m^2 BGF	-	**7**	-	-	**0,4**	-
490	Construction area	m^2 BGF	-	**0**	-	-	**0,0**	-

Table 55: Planning Parameters of Level 2 breakdown [32] (building type: industrial production building, mainly skeleton structure)

KG	**Cost groups to the 2nd level**	**Unit**	min	**Amount/NF**	max	min	**Amount/BGF**	max
310	Excavation	m^3 BGI	1,30	**1,38**	1,38	1,03	**1,14**	1,14
320	Foundation	m^2 GRF	0,68	**0,83**	0,88	0,57	**0,70**	0,76
330	Outer walls	m^2 AWF	0,50	**0,59**	0,63	0,39	**0,48**	0,54
340	Inner walls	m^2 IWF	0,40	**0,50**	0,66	0,32	**0,41**	0,50
350	Ceiling	m^2 DEF	0,24	**0,32**	0,55	0,19	**0,25**	0,42
360	Roof	m^2 DAF	0,70	**0,84**	0,89	0,59	**0,71**	0,76