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System Analysis & Evaluation of Greenhouse Modules within Moon/Mars Habitats

Paul Zabel

Zum
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Betreuer:	Dr.-Ing. Tino Schmiel, ILR TU-Dresden Dipl. Wi.-Ing. Daniel Schubert, DLR Bremen
Verantwortlicher Hochschullehrer:	Prof. Dr. Martin Tajmar, ILR TU-Dresden
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Zweiter Gutachter:	Dipl. Wi.-Ing. Daniel Schubert, DLR Bremen

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Abstract

Long term or even permanent settlement on different planets of the solar system is a fascination for mankind. Some researchers contemplate that planetary settlement is a necessity for the survival of the human race over thousands of years. The generation of food for self-sufficiency in space or on planetary bases is a vital part of this vision of space habitation. The amount of mass that can be transported in deep space missions is constrained by the launcher capability and its costs.

The space community has proposed and designed various greenhouse modules to cater to human culinary requirements and act as part of life support systems. A survey of the different greenhouse space concepts and terrestrial test facilities is presented, drawing a list of measurable factors (e.g. growth area, power consumption, human activity index, etc.) for the evaluation of greenhouse modules. These factors include tangible and intangible parameters that have been used in the development of an evaluation method on greenhouse concepts as a subsystem of planetary habitats.

Überblick

Permanente Ansiedlungen auf anderen Planeten unseres Sonnensystems faszinieren die Menschheit schon seit langem. Einige Forscher behaupten sogar, dass Siedlungen auf anderen Planeten für das Überleben der Menschheit über Tausende von Jahren notwendig sind. Die Erzeugung von Nahrung im Weltraum oder in planetaren Habitaten ist für die Selbstversorgung der Crew unverzichtbar und ein essentieller Bestandteil aller Visionen von extraterrestrischen Kolonien. Ohne Selbstversorgung sind zukünftige Habitate auf Lieferungen von der Erde angewiesen, die jedoch durch die Kapazität der Trägersysteme und die entstehenden Kosten begrenzt sind.

Zahlreiche Entwürfe für Greenhouse-Module als Nahrungsquelle und Teil der Lebenserhaltungssysteme planetarer Habitate wurden bereits von Wissenschaftlern vorgeschlagen. In der vorliegenden Arbeit wird eine Erfassung verschiedener Greenhouse-Konzepte und terrestrischer Testanlagen durchgeführt. Weiterhin erfolgt die Erstellung einer Liste messbarer Vergleichsfaktoren (z.B. Anbaufläche, Energiebedarf). Die Faktoren beinhalten quantitative und qualitative Parameter und werden für die Bewertung ausgesuchter Greenhouse-Konzepte mit einer geeigneten Bewertungsmethode genutzt.

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List of Abbreviations

AC	**A**gricultural **C**riteria
ACMG	**A**rthur **C**larke **M**ars **G**reenhouse
ACS	**A**tmosphere **C**ontrol **S**ubsystem
AGA	**A**rrangement of **G**rowth **A**rea
AHP	**A**nalytic **H**ierarchy **P**rocess
AIC	**A**daptability of **I**nternal **C**onfiguration
AlGaInP	**Al**uminum **Ga**llium **In**dium **P**hosphide
ALS	**A**dvanced **L**ife **S**upport
AR	**A**ir **R**evitalization
ASC	**As**tro**c**ulture
AtC	**A**tmospheric **C**omposition
AU	**A**stronomical **U**nit
BIO-Plex	**Bio**regenerative **P**lanetary **L**ife Support Systems Test Compl**ex**
BLSS	**B**iological **L**ife **S**upport **S**ystem
BPC	**B**iomass **P**roduction **C**hamber
BPS	**B**iomass **P**roduction **S**ystem
BVAD	**B**aseline **V**alues and **A**ssumptions **D**ocument
CDHS	**C**ommand & **D**ata **H**andling **S**ubsystem
CEEF	**C**losed **E**cology **E**xperiment **F**acilities
CELSS	**C**ontrolled **E**cological **L**ife **S**upport **S**ystem
CI	**C**onsistency **I**ndex
CM	**C**rew **M**ember
CPBF	**C**ommercial **P**lant **B**iotechnology **F**acility
CR	**C**onsistency **R**elationship
CSA	**C**anadian **S**pace **A**gency
DLR	**D**eutsches Zentrum für **L**uft- und **R**aumfahrt
DNA	**D**eoxyribo**n**ucleic **A**cid
EC	**E**nvironmental **C**riteria
ECLSS	**E**nvironmental **C**ontrol and **L**ife **S**upport **S**ubsystem
EER	**E**nergy **E**fficiency **R**atio
EPS	**E**lectrical **P**ower **S**ubsystem
ESM	**E**quivalent **S**ystem **M**ass
EVA	**E**xtra **V**ehicular **A**ctivity

FARM	**F**ood **a**nd **R**evitalization **M**odule
FC	**F**undamental **C**riteria
FP	**F**ood **P**rovision
GaN	**Ga**llium **N**itride
GHM	**G**reen**h**ouse **M**odule
GM	**G**rowth **M**edium
HCS	**H**arvest & **C**leaning **S**ubsystem
HID	**H**igh **I**ntensity **D**ischarge
HMPRS	**H**aughton **M**ars **P**roject **R**esearch **S**tation
HPS	**H**igh **P**ressure **S**odium
IC	**I**nterface **C**riteria
InGaN	**In**dium **Ga**llium **N**itride
ISS	**I**nternational **S**pace **S**tation
JSC	**J**ohnson **S**pace **C**enter
LA	**L**evel of **A**utomation
LCS	**L**ighting **C**ontrol **S**ubsystem
LED	**L**ight **E**mitting **D**iode
LGH	**L**unar **G**reen**h**ouse
LPS	**L**ow **P**ressure **S**odium
LS	**L**ighting **S**trategy
LT	**L**ighting **T**ype
MA	**M**orphological **A**nalysis
MH	**M**etal **H**alide
MS	**M**odule **S**tructure
NASA	**N**ational **A**eronautics and **S**pace **A**dministration
NDS	**N**utrient **D**elivery **S**ubsystem
P/C	**P**hysico-**C**hemical
PAR	**P**hotosynthetically **A**ctive **R**adiation
PCDS	**P**ower **C**ontrol & **D**istribution **S**ubsystem
PCS	**P**lant **C**ultivation **S**ubsystem
PGBA	**P**lant **G**eneric **B**ioProcessing **A**pparatus
PGC	**P**lant **G**rowth **C**hamber
PGF	**P**lant **G**rowth **F**acility
PGU	**P**lant **G**rowth **U**nit

Phoebe	**P**ermanent **H**uman M**o**on **E**xploration **B**as**e**
PM	**P**lant **M**ixture
PPF	**P**hotosynthetic **P**hoton **F**lux
PS	**P**lanting **S**equence
R	**R**andom **C**onsistency
RD	**R**esupply **D**ependency
RH	**R**elative **H**umidity
RMD	**R**eference **M**issions **D**ocument
SCV	**S**pecific **C**ultivation **V**olume
SEEDS	**S**pac**e** **E**xploration and **D**evelopment **S**ystems
SI	**S**ystème **I**nternational d' unites (**I**nternational **S**ystem of Units)
SMS	**S**tructures & **M**echanisms **S**ubsystem
TC	**T**emperature **C**ontrol
TCS	**T**hermal **C**ontrol **S**ubsystem
TEC	**T**hermal **E**lectric **C**ontroller
UA-CEAC	**U**niversity of **A**rizona's **C**ontrolled **E**nvironment **A**griculture **C**enter
UV	**U**ltra**v**iolet
WCS	**W**ater **C**ontrol **S**ubsystem
WCSAR	**W**isconsin **C**enter for **S**pace **A**utomation and **R**obotics
WP	**W**ater **P**urification

1 Introduction

1.1 Motivation and Structure of Work

The continuous provision of food for the crew in spacecraft around or even beyond Earth is a challenge. Today's astronauts are addicted on resupply vessels from Earth to get provided with food. The launch costs of resupply vessels are generally high and therefore, the launches occur rarely and only when necessary. Therefore, the provision of fresh fruit and vegetables is limited to the time after the arrival of resupply. Consequently, today's space dishes mainly consist of dehydrated and thermo-stabilized food. However, a diet high in fresh fruit and vegetables provides excellent nutrition content to help maintain the health and well-being of astronauts and cosmonauts, whilst also providing significant benefits on the crew's psychological health.

The production of food during crewed space missions can reduce the required resupply mass for short duration missions and are an asset for long duration missions to other planetary bodies of our solar system. Until now several experiments were conducted in this research field and several terrestrial test facilities of greenhouse modules exist. In addition a large number of conceptual designs of greenhouses for food production in space are published. Some of them are simple concepts, while others are detailed designs including calculations and simulations.

One task of this thesis is the establishment of a comprehensive list of plant growth chambers, greenhouse module concepts and terrestrial test facilities. A methodology for the analysis and evaluation of greenhouse modules will be developed. Therefore, a comprehensive list of measurable factors will be implemented. The proposed methodology will be tested on selected greenhouse modules.

Scientific background related to greenhouse modules is investigated in Chapter 2. The environmental conditions in free space and on Moon and Mars are explained in the first subchapter, followed by the listing of metabolic and physiological requirements of humans in the second subchapter. Greenhouse modules are usually part of the environmental control and life support subsystem (ECLSS) of spacecraft or planetary habitats. Consequently, the different types of ECLSS are investigated during this thesis, see the third subchapter. An overview over past and present food provision during space mission is given in the fourth subchapter. A greenhouse module subsystem definition is provided in the fifth subchapter.

Another task of this thesis is the development of an analysis and evaluation strategy. Chapter 3 explains the developed analysis and evaluation methodology in the first subchapter. The selected analysis method, the Morphological Analysis, is described in the second subchapter. The third subchapter provides two suitable methods for the evaluation of greenhouse module, the Equivalent System Mass (ESM) concept and the Analytical Hierarchy Process (AHP). The ESM concept was developed by NASA researchers to evaluate different ECLSSs, while the AHP is a more general evaluation method. The fourth subchapter establishes measurable factors related to greenhouse modules. Therefore, the proposed factors are categorized in four major sections, fundamental, environmental, agricultural and interface factors. A detailed description for each factor is provided by the fourth subchapter. Finally, the AHP is selected for an exemplary evaluation of greenhouse module concepts.

A demonstration of the developed methodology is executed in Chapter 4. The first subchapter offers a list of flown plant growth chambers, greenhouse module concepts and terrestrial test facilities. Furthermore, three greenhouse modules are selected for the demonstration and a detailed description is given for each. The second subchapter defines the goal of the exemplary evaluation. In the third subchapter evaluation criteria are selected out of the previously established compilation of measurable factors and formed to a criteria hierarchy. Afterwards the selected criteria are weighted for the following AHP. Therefore, local and global weighting values for each element of the hierarchy are calculated. The fourth subchapter provides the result of the evaluation of the three selected greenhouse modules based on the previously established weightings.

Chapter 5 discusses the results of this thesis and describes potential future tasks for the improvement of the developed methodology.

In Chapter 6 a summary of this thesis is given.

1.2 Previous Work

This thesis is part of the greenhouse research efforts expedited by the department of System Analysis Space Segment of the Institute of Space System of the German Aerospace Center (DLR) Bremen. During the last few years the research plans are evolved and preliminary research in the field of greenhouse modules was conducted.

The goal of the efforts is to enforce the research in bio-regenerative life support systems with the focus on food production with greenhouse modules. However, the ability of plants to purify water, absorb carbon dioxide and generate oxygen will be investigated too. Therefore, the system analysis of existing greenhouse module concepts and terrestrial test facilities is an essential part to determine advantages and disadvantages of different subsystem solutions. The design, construction and testing of a high-efficient food producing greenhouse module is the long term target of the research conducted by the greenhouse project team of the DLR Bremen.

Bachelor, master and diploma thesis related to different topics of the research field were supervised by the researchers of the DLR Bremen during the last year. Leigh Glasgow from the Cranfield University finished his master thesis in July 2011. His task was the development of a phase A design of an innovative greenhouse. Muhammad Shoaib Malik also from the Cranfield University analyzed power and illumination subsystems suitable for the lighting of plants in greenhouse modules in his master thesis, September 2011. Markus Dorn from the University of Applied Science in Dresden investigated plant species and cultivation methods for the usage in greenhouse modules for space application during his bachelor thesis. He finished his work in September 2011.

Besides the author of this thesis, three other students are currently working on their thesis regarding greenhouse modules at the DLR Bremen. Thereby, a market analysis for the use of greenhouse modules in different terrestrial areas is executed and investigations in the monitoring of plant development and growing are accomplished.

Plans for the design and construction of a laboratory at the DLR Bremen for further research in the field of greenhouses are becoming concrete. Thereby, systems for greenhouse modules will be developed and their influence on plant development and growing will be investigated.

2 Scientific Background

Chapter 2 provides fundamental scientific background required for the following parts of this thesis. In the first subchapter the environmental conditions in free space, on Moon and on Mars are summarized. The second subchapter describes the physiological, metabolic and other requirements for the survival of human beings. In the third subchapter an overview over Environmental Control and Life Support Systems is given. The fourth subchapter describes the development of food provision during the last decades. The fifth subchapter defines the different subsystems of greenhouse modules and explains their functions.

2.1 Environmental Conditions

2.1.1 Free Space Environment

The environment in free space is different from that on Earth. This topic is extensively discussed in several publications. However, in this subchapter the effects of

- magnetic fields,
- radiation,
- vacuum and
- gravity

in free space are briefly described.

Magnetic fields in free space are originated by planets, stars or other celestial bodies. The intensity of magnetic fields lowers with increasing distance from the origin. Consequently, effects of magnetic fields on spacecraft have to be considered wisely in close range or on the surface of celestial bodies. According to reference [**1**], the trapped charged particles in the magnetosphere of celestial bodies, like the Van Allen belts around Earth, has the main effect on spacecraft. Furthermore, magnetic fields interact with spacecraft and cause magnetic induction in their systems. That has to be considered during the design process [**1**].

In reference [**1**] *radiation* is defined as all kinds of particle and wave radiation, and can be divided into electromagnetic and ionizing radiation. The electromagnetic radiation is the combination of rays of the whole spectrum: gamma-rays, X-rays, UV, visible light, infrared and radio waves. Inside the solar system nearly the whole electromagnetic radiation is emitted by the Sun. However, in close range to planets, moons, asteroids and comets the radiation emitted by them affects the spacecraft too. The energy density of the electromagnetic radiation of the Sun at a distance of one Astronomical Unit (AU) from the Sun is 1368 W/m² [**1**].

The ionizing radiation consists of solar cosmic rays, galactic cosmic rays and the Van Allen Belts in the near Earth environment. The solar cosmic rays are produced by the sun as solar wind or solar flares and mainly consist of protons and electrons. The galactic cosmic rays are emitted by distant stars and galaxies and contain high energetic heavy particles like protons, α-particles and heavy nuclei. The Van Allen belts are regions in the Earth magnetic field, where high energetic electrons and protons are caught and oscillate along the magnetic field lines. The interaction of high energetic radiation with living cells can cause physical damage to the cells and mutations of the DNA. On Earth humans, animals and plants are protected against the effects of cosmic radiation by the magnetic field and the atmosphere. In free space environment, living creatures have to be protected against the effects of radiation. Furthermore, the impact of radiation on structural materials has to be considered in the design of spacecraft [**1**].

According to reference [**1**], the *vacuum* in free space influences the heat transfer and the materials of spacecraft. Due to the very low density of particles in free space, convective and conductive heat transfer between the spacecraft and the environment are negligible. However, conductive heat transfer between parts of the spacecraft exists. Consequently, spacecraft can emit and absorb heat only via radiation. That has to be considered in the design process of spacecraft. In addition to the impact of vacuum on the heat transfer mechanisms, it also affects the materials of spacecraft. Three different physical and chemical processes are responsible for changes in materials: outgassing, sublimation and diffusion. Due to the outgassing, materials lose gaseous components. Sublimation is problematic for materials with a high vapor pressure: the higher the vapor pressure, the more the mass loss. Outgassing and sublimation can result in a lower stiffness, hardness and durability. Solid materials without a gas layer between them can be affected by cold welding caused by diffusion of atoms of the used materials into each other; this can result in malfunctions of mechanisms [**1**].

Humans, animals and plants originated on Earth are adapted to the existent *gravity* field. Therefore, reference [**1**] declares the state of microgravity in free space as the most dramatic environmental condition. Reduced gravity causes several effects on the human body, e.g. bone mass and muscle loss. Plants are also affected by reduced gravity. Due the failure of the gravity-sensing system the plants can lose their normal relative orientation of shoot and root. The gravitational force of the Earth can be imitated by spacecraft, due to the rotation of sections with a defined angular velocity resulting in a centripetal acceleration [**1**].

2.1.2 Local Environment of Moon and Mars

The properties of other planets and moons and the conditions on their surfaces vary from the Earth's. Moon and Mars are probable targets for the first long-time or even permanent crewed base. Therefore, this subchapter describes the properties and environmental conditions of Moon and Mars and compares the conditions to that on Earth. The general properties, the magnetic field, the radiation, the atmosphere, the surface temperature as well as the composition of the local soil are discussed. A comparison of properties between Earth, Moon and Mars is shown in Table 2-1.

The *Moon* is the sole natural satellite orbiting around Earth. According to reference [**2**], he has a radius of 1738 kilometers and surrounds the Earth in a mean distance of 384400 kilometers in 27.32 days. The Moon's gravity constant has a value of 1.62 m/s^2; this is around one sixth of the Earth's. Earth and Moon have the same mean distance from the Sun; hence both have the same mean solar constant of 1368 W/m^2. However, opposed to Earth the Moon's day and night at the equator have a length of 14 Earth days each [**1**]. The poles of the Moon are subject to a half-year day-night-cycle. Due to the low gravity, the Moon cannot maintain an atmosphere. The temperature on the surface at the equator ranges from 120 °K during night to 380 °K during day [**2**]. Nevertheless, at the poles the temperature can fall to 40 °K in permanently shaded craters [**1**]. As a consequence of absent atmosphere and magnetic field, the Moon receives twice as much UV radiation the Earth does and a higher amount of ionizing radiation. The lunar soil consists of 42 % oxygen, 21 % silicone, 13 % iron, 8 % calcium, 7 % aluminum and 6 % magnesium. Usually, these elements are bound in oxides. Basically it is feasible to extract hydrogen, oxygen, water and other useful materials out of the soil, but the processes require either high power or high temperatures [**1**].

Mars is the fourth planet of our solar system as seen from sun. He surrounds the Sun in 686.98 days in a distance of 1.54 AU [**1**]. Phobos and Demios are the names of the two moons orbiting around the Mars. The Martian equatorial radius is around 3396 kilometers. Due to the higher distance from the Sun, the mean intensity of the solar radiation is 615 W/m^2. However, the orbit of Mars is more eccentric than the Earth's; hence the solar constant varies from 493 W/m^2 at aphelion to 718 W/m^2 at perihelion [**1**]. Mars possesses a thin atmosphere consisting of 95.3 % carbon dioxide, 2.7 % nitrogen and 1.6 % argon. The mean surface pressure of the atmosphere is around 6 mbar [**3**]. The mean surface temperature is 210 °K, but the temperature varies from 130 °K to 300 °K, depending on the region [**1**]. Due to the thin atmosphere and the low concentration of ozone, the UV radiation reaching the Martian surface is higher than reaching the surface of the Earth. Mars maintains a magnetic field, but it is not strong enough to keep the particles of ionizing radiation outside the atmosphere. The atmosphere itself provides protection against ionizing radiation, but the level of protection varies with the composition and dimension of the atmosphere [**1**]. The Martian soil consists of 43 % oxygen, 21 % silicone, 13 % iron, 8 % potassium, 5 % magnesium, 4 % calcium, 3 % aluminum and 3 % sulfur [**1**].

Table 2-1: Properties of Earth, Moon and Mars

	Earth	**Moon**	**Mars**
Equatorial Radius	6378 km	1738 km	3396 km
Mean Surface Gravity	9.81 m/s^2	1.62 m/s^2	3.72 m/s^2
Mean Distance from Sun	149.6 * 10^6 km	149.6 * 10^6 km	227.9 * 10^6 km
Mean Solar Constant	1368 W/m^2	1368 W/m^2	615 W/m^2
Atmospheric Composition	78 % N_2 21 % O_2 0.93 % CO_2	none	95.3 % CO_2 2.7 % N_2 1.6 % Ar
Mean Surface Pressure	1 bar	3 * 10^{-15} bar	0.006 bar
Mean Surface Temperature	288 °K	day: 380 °K night: 120 °K	210 °K
Reference	[**4**]	[**2**]	[**3**]

2.2 Human Requirements

In this subchapter the requirements of humans are summarized, which are divided into physiological, metabolic and miscellaneous requirements. Temperature, relative humidity, pressure and composition of the atmosphere are physiological requirements, while food and water are metabolic requirements. The miscellaneous requirements are the result of the effects of light, radiation, noise, vibration and human factors.

Physiological requirements are necessary for the survival of human beings and have to be guaranteed at any time. Basically, humans can resist a wide span of temperature assuming optimal clothing. For long durations an ambient temperature from 18.3 to 26.7 °C is the optimal zone for humans, in which their performance of routine activities is not affected by thermal stress [**5**]. Relative humidity stands in close relation to the temperature. The optimal relative humidity of the ambient air is between 25 % and 70 % [**6**]. Is the relative humidity below 25 %, the air is too dry to maintain nominal functioning of mucous membranes over a long duration. Exceeds the relative humidity the limit of 70 %, the crew comfort is reduced and the condensation of water on surfaces is increased [**5**]. The combination of the optimal temperature range and the optimal humidity range forms the comfort box for humans, as seen in Figure 2-1.

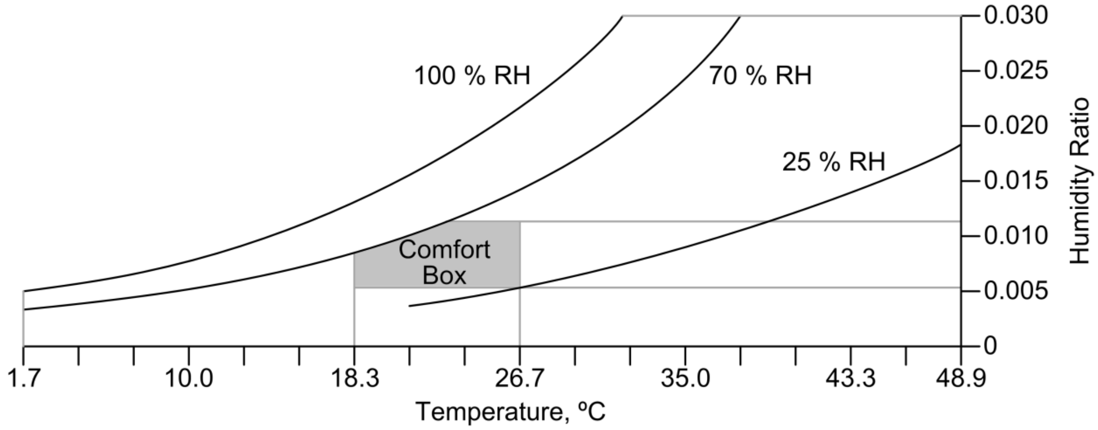


Figure 2-1: Temperature and humidity ranges for best comfort of humans [6**]**

Atmospheric pressure and composition are basic requirements to allow human lungs to provide enough oxygen for all organs and functions of the human body. Thereby, a strong relation between the absolute atmospheric pressure and the partial oxygen pressure exist. Figure 2-2 illustrates the relationship between the percentage of oxygen and the total air pressure of a breathable atmosphere. Is the partial pressure of oxygen too low, humans are affected by hypoxia, while they suffer from hyperoxia when the partial pressure is too high [**7**]. For long term space missions an Earth-like atmospheric composition and pressure is suitable. Therefore, the total air pressure of manned spacecraft should range from 99.9 to 102.7 kPa with a partial oxygen pressure of 19.5 to 23.1 kPa and a partial nitrogen pressure of 79 kPa. The ECLSS has to assure, that the partial pressure of carbon dioxide does not exceed 0.4 kPa [**6**]. A higher carbon dioxide percentage results in increased respiration, heart rate, blood flow to brain as well as hearing loss, mental depression, headache, dizziness, nausea, decreased visual discrimination and unconsciousness [**6**].

For maintaining the atmospheric requirements it has to be considered, that humans convert oxygen to carbon dioxide. Humans need a definite amount of oxygen per day, depending on their activity level, sex, and size. The relation is shown in Table 2-2. The amount of required oxygen ranges from 0.52 to 1.11 kg per person and day [**8**]. The carbon dioxide output of humans is between 0.726 and 1.226 kg per person and day [**6**].

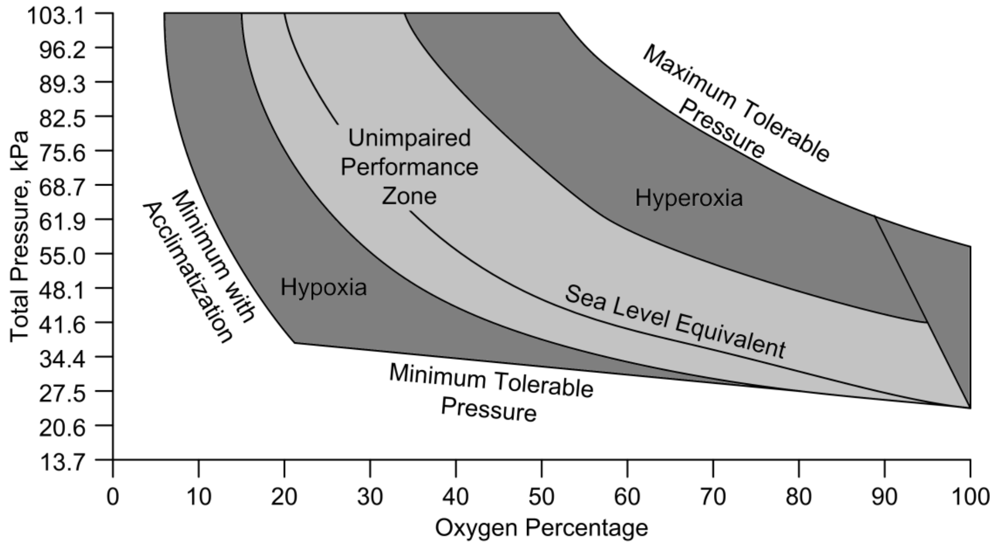


Figure 2-2: Breathable percentage of oxygen as a function of total pressure [7]

The *metabolic* requirements are demands of humans for missions that last longer than a few hours. The metabolic load of a person depends on his/her activity level, sex and, age, body mass and height. Exemplary values for the metabolic load of different activity levels are shown in Table 2-2. However, the metabolic load is calculated with the equation for the Energy Efficiency Ratio (EER) for men 19 years and older [**5**]:

$$\mathrm{EER}\,[\mathrm{kcal/d}] = 622 - 9.53 * \mathrm{Age}\,[\mathrm{y}] + \mathrm{Activity\ Level} * (15.9 * \mathrm{Body\ Mass}\,[\mathrm{kg}] + 539.6 * \mathrm{Height}\,[\mathrm{m}]) \tag{1}$$

and for women 19 years and older with the equation:

$$\mathrm{EER}\,[\mathrm{kcal/d}] = 354 - 6.91 * \mathrm{Age}\,[\mathrm{y}] + \mathrm{Activity\ Level} * (9.36 * \mathrm{Body\ Mass}\,[\mathrm{kg}] + 726 * \mathrm{Height}\,[\mathrm{m}]). \tag{2}$$

Table 2-2: Human metabolic load and oxygen requirements [8]

Activity level	**Metabolic Load [kcal/(CM*d)]**	**Oxygen Requirements [kg/(CM*d)]**
Low Activity	2618	0.78
Nominal Activity	2822	0.84
High Activity	3223	0.96
5th Percentile Nominal Female	1812	0.52
95th Percentile Nominal Male	3718	1.11

The demands of water and food per day depend on the metabolic load. According to reference [**8**], the daily fluid intake can be assumed from 1.0 to 1.5 milliliters per kcal. However, the minimum fluid intake has to be at least 2 liters per person and day. Reference [**5**] declares, that 50 to 55 % of the daily energy intake shall be provided by carbohydrates. Thereby, complex carbohydrates (e.g. starches) have to be preferred and simple sugars should not exceed 10 % of the total carbohydrate intake. Furthermore, 12 to 15 % [**8**] and not more than 35 % [**5**] of the daily energy intake has to be delivered by proteins. The suitable ratio of animal and plant based proteins is 3:2. Higher and lower intakes of proteins can amplify space-induced musculoskeletal changes. The daily energy intake provided by fat should range from 25 to 35 % [**5**] with a ratio of 1:1.5 to 2:1 for polysaturated, monosaturated and saturated fat [**8**]. A detailed compilation of the daily energy intake through macronutrients (carbohydrates, protein, fat, cholesterol and fiber) is shown in Appendix 2-1. In addition to macronutrients humans require several micronutrients like vitamins and minerals. A detailed list of the recommended intake of them is shown in Appendix 2-2: Recommended Micronutrient Daily Dietary Intake. Altogether each person needs 0.5 to 0.86 kg (dry mass) food per day [**6**].

Besides the physiological and metabolic requirements are others, which are grouped under *miscellaneous* requirements. The necessities of humans for light, radiation shielding, noise and vibration protection as well as human factors are part of this group. The description of these requirements is neglected by this thesis. However, the references [**5**] and [**8**] provide further information about this topic.

2.3 Environmental Control and Life Support Systems

The Environmental Control and Life Support System (ECLSS) is a subsystem of crewed spacecraft. The task of the ECLSS is the maintenance of all human requirements, as discussed in the previous subchapter, to assure the survival, optimal work performance and comfort of the crew. According to reference [**9**], the ECLSS can be split into the functional parts atmosphere management, water management, food supply and waste management, as shown in Figure 2-3. However, the systems for crew safety and Extravehicular Activities (EVAs) are also part of the ECLSS.

The *atmosphere management* maintains the desired percentage of nitrogen and oxygen for the crew and removes the carbon dioxide from the air. Furthermore, this part of the ECLSS controls the temperature, humidity and pressure of the atmosphere. The ventilation and filtration of the air is also a function of the atmosphere management.

The *food supply* has to provide enough nourishment to assure the desired daily nutritional intake of each crewmember. The production, processing, storage and distribution of the food are also tasks of this part of the ECLSS.

The *water management* is responsible for the provision, storage and distribution of potable and hygiene water with the anticipated temperature. It has also the duty of filtering the water and treating the liquid feces of the crew.

The *waste management* stores and recycles the solid feces of the crew, the waste of food production, packaging, expendable parts and residual substances from payloads and water processing.

The *crew safety* consists of several functions, which provide welfare for the crew. Parts of the crew safety are systems for fire detection and suppression as well as shielding against radiation, micrometeoroids and space debris. In addition the crew safety is responsible for the treating of contaminations inside spacecraft.

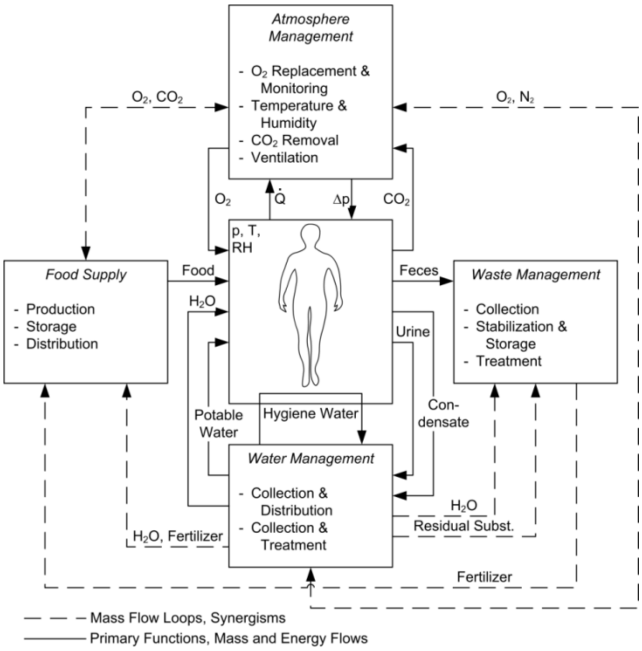


Figure 2-3: Tasks and interfaces of life support systems [9**]**

Environmental Control and Life Support Systems can be classified on their required relative supply mass as open, partly closed or closed loop systems. Crewed spacecraft with an open loop ECLSS need a constant resupply of all goods required for the survival of the crew, see Figure 2-4 (derived from table IV.2 of reference [**6**]). Traditionally, open loop ECLSS are used in transfer vehicles and during short missions. The ECLSS of the Vostok, Voskhod, Soyuz, Mercury, Gemini and Apollo casuples are examples for open loop systems. Partly closed ECLSS can be achieved by closing the water, oxygen and carbon loops. Each closed loop reduces the required relative resupply mass. The closure of the water loop due to the recycling of the waste and wash water reduces the relative supply mass to 45 %. A regenerative carbon dioxide absorption and the production of oxygen out of carbon dioxide reduce the relative resupply mass by 15 %, respectively 10 % [**6**]. An exemplary partly closed system is the International Space Station (ISS). Due to the closing of the carbon loop by the use of food production from recycled wastes and the elimination of all leakage and needs of spare parts, a closed loop ECLSS can be implemented. Currently, no closed ECLSS for space application exists. However, some terrestrial testbeds achieved nearly closed ECLSS for a limited duration. A detailed analysis of this testbeds can be found in Chapter 4.1.

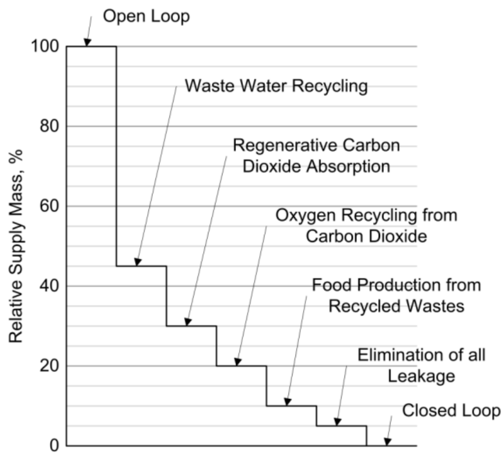


Figure 2-4: Reduction of relative supply mass by successive loop closure [6**]**

Closure of the individual loops can be achieved with Physico-Chemical (P/C) or Biological Life Support Systems (BLSS). Physico-chemical life support systems use physical or chemical processes to fulfill the tasks of an ECLSS. They are capable of accomplishing the tasks of the atmosphere, water and waste management and close the water and oxygen loop [**10**]. Several technologies for P/C life support systems exist. Available P/C systems for the water management are shown in Appendix 2-3: P/C Technologies for the Water Management, while P/C technologies for air revitalization are shown in Appendix 2-4: P/C Technologies for Air Revitalization. P/C systems are not capable to produce food, therefore, biological systems are necessary. A BLSS uses plants, algae or other creatures to produce food and fulfill the tasks of the atmosphere, water and waste management. However, the design and operation of a BLSS is complex and the mass of such systems is high. When a combination of P/C systems and BLSS are used in a crewed spacecraft, the ECLSS is a hybrid system, while a life support system containing only BLSS is called Controlled Ecological Life Support System (CELSS). Figure 2-5 shows the cumulative mass of different forms of ECLSS as a function of the mission duration, and the break even points at which one system is more suitable than another [**11**].

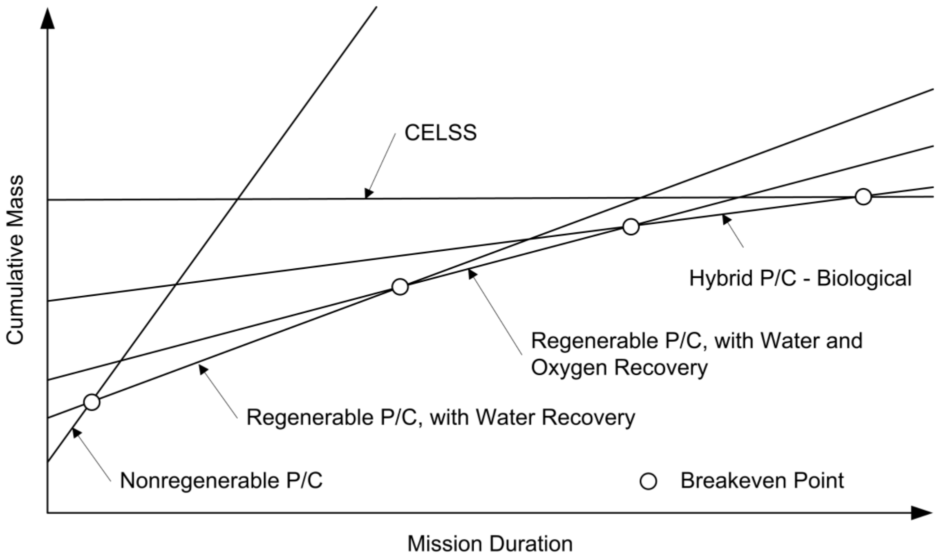


Figure 2-5: Cumulative mass of different ECLSS as a function of mission duration [11**]**

Hence, nonregenerable systems are only applicable for short duration missions, regenerable P/C systems are suitable for mid duration mission, and hybrid or CELSS are required for long duration missions like permanent bases on other planets.

2.4 Survey on Past and Present Food Provision in Crewed Spacecraft

The food provision for humans in crewed spacecraft changed in the past decades with the increasing mission duration. This subchapter illustrates the evolution of food provision systems from Apollo to the space stations Mir and ISS. According to reference [**12**], the provision of high nutritional, well-balanced food for all members of the crew is important to assure their welfare and possibility to work in space and during Extravehicular Activities (EVAs). Food for astronauts has to be easy to prepare, but still attractive to eat. Furthermore, the food must be small in volume, low in weight and low in waste to reduce launch and operation costs. Besides the delivery of nutrients, food preparation, cooking and eating together are important social events for the crew of spacecraft. Therefore, a suitable eating place is required inside the spacecraft [**12**].

The *Apollo* spacecraft were designed for crewed missions to the Moon, including a landing and EVAs on the lunar surface. The crew of an Apollo mission consisted of three astronauts; two of them were assigned for the lunar surface mission segment. The whole mission time was supposed to be not longer than 14 days. The food system design for the Apollo spacecraft was based on the experiences of the Mercury and Gemini programs [**12**]. Food during the Apollo missions was available in four different forms, bite-sized, rehydratables and semisolid thermostabilized food, and beverage powder. The bite-sized food was dehydrated small cubes with different tastes like meat, cheese and fruits. The cubes were rehydrated with saliva inside the mouth. Rehydratables were precooked and dehydrated meals, which could be rehydrated with water in less than 15 minutes. Tuna, salmon or chicken salads, and shrimp cocktail were available as rehydratables. The semisolid thermostabilized food was served in flexible metal tubes and consisted of high-nutrient fluids. Figure 2-6 shows a typical Apollo food package. Inside the Apollo spacecraft was no dedicated area for food preparation and consumption. However, the food provision evolved during the Apollo program. During later missions new kinds of flavors were introduced and sandwiches were available too [**12**].

The food for the Soviet *Salyut* missions was prepared to last up to 18 months and consisted primarily of canned, dehydrated and in aluminum tubes stored meals. The meals rotated in a six day cycle. In addition to the food the cosmonauts took vitamin pills. Fresh food was sometimes provided by visiting crews. During the Salyut missions several small plant growth chambers were tested for the usage of growing fresh food in space [**12**]. The food of the Salyut program has improved over time. From Salyut 7 on a pantry system replaced the precooked and packed food. A folding table for preparing and eating food was installed inside the work compartment. Two electrical ovens and tools for the meal preparation were also included in the eating table. Furthermore, the cosmonauts were allowed to select their food by themselves within a calculated caloric ratio [**12**].

According to reference [**12**], the American *Skylab* space station had a dedicated food processing and eating area, the wardroom. Figure 2-7 shows the Skylab food tray, which could be placed into a table inside the wardroom, which was located in the center, so that all three crewmembers could eat together at the same time. In addition to the table and food preparing tools, the wardroom had a freezer and a refrigerator. The astronauts were able to select their food from rehydratables, thermostabilized and frozen meals. Beverages were also available. Each astronaut had his own food tray, where they could heat their meals individually. The trays consisted of four small and four large openings for holding the food packages, and one opening to hold a plastic bottle filled with beverages. Three of the large openings were able to heat the food packages [**12**].

Figure 2-6: Apollo space food [13**]**

Figure 2-7: Skylab food tray [13**]**

During the missions of the *Space Shuttle* the food of the astronauts consisted of rehydratables, thermostabilized, irradiated and fresh food. The astronauts could select their menu several months before the flight. They were able to combine meals out of over 200 food items. After the selection, the meals were analyzed on their nutritional content and corrected by NASA physicians. The usual short mission durations allowed the provision of a variety of fresh food, such as bread, fruits and vegetables. The fresh food was stored inside the fresh food locker. Each crewmember had his own locker tray which contained his meals. On the middeck of the Shuttle a galley rack was installed, which included an oven, a rehydration unit, a water dispenser for hot and cold water, and the provision of hygiene water. There was no dedicated eating area inside the Space Shuttle. Astronauts had to use a food service tray attached to their legs to prepare their food [**12**], see Figure 2-8.

The food consumed on board the *Mir* space station was storable for up to 18 months due to dehydration. Usually, the food was chopped in bite-sized pieces and packed in plastic bags. The periodic resupply with Progress spacecraft allowed the delivery of fresh food for the Mir crew. The cosmonauts were allowed to select their food for each day, as long as it met the nutritional requirements. In addition to the food, vitamins were applied due taking pills. Inside the Mir base block a food cabinet existed, which included a refrigerator and an eating table. The table was used to prepare the meals. The Russians continued their research in plant growth chambers and small greenhouses for space applications. Therefore, several plant growth chambers were tested aboard the Mir station. These chambers provided some fresh food for the crew [**12**].

Figure 2-8: Space Shuttle food tray [13**]**

Figure 2-9: ISS food container [13**]**

The *ISS* food facility is similar to the Mir's, because of its location inside the Russian Zvezda module. It consists of a table, hot water dispenser, food storage and heaters. Usually, the meals are a combination of thermostabilized rehydratables, intermediate moisture, and precooked, fresh and irradiated food. Beverages are also provided. Each crewmember can create an own menu, based on a 16-day rotation. Therefore, several food items from Russia, USA, Europe and Japan can be combined. In addition to the normal meals, each crewmember has a bonus container which can be filled with any food that meets the microbiological requirements [**12**]. Figure 2-9 shows a filled food container for the ISS.

2.5 Greenhouse Module Subsystems

2.5.1 Classification

Comparable to spacecraft, greenhouse modules can be divided into several subsystems. However, the existing greenhouse module subsystem classifications are not consistent, because each research team established their own nomenclature. Consequently, this chapter describes the classification of greenhouse module subsystems used in this thesis. The selected approach is a fundamental classification, in which every subsystem has its own tasks. Nevertheless, some subsystems could be merged, because of their close relations to each other.

The ten subsystems of greenhouse modules are the Plant Cultivation Subsystem (PCS), the Nutrient Delivery Subsystem (NDS), the Harvest & Cleaning Subsystem (HCS), the Atmosphere Control Subsystem (ACS), the Water Control Subsystem (WCS), the Lighting Control Subsystem (LCS), the Thermal Control Subsystem (TCS), the Structures & Mechanisms Subsystem (SMS), the Power Control & Distribution Subsystem (PCDS) and the Command & Data Handling Subsystem (CDHS). They can be assigned to three groups of subsystem, as shown in Figure 2-10. The groups are named Agricultural Subsystems, Environmental Control Subsystems and Fundamental & Interface Subsystems.

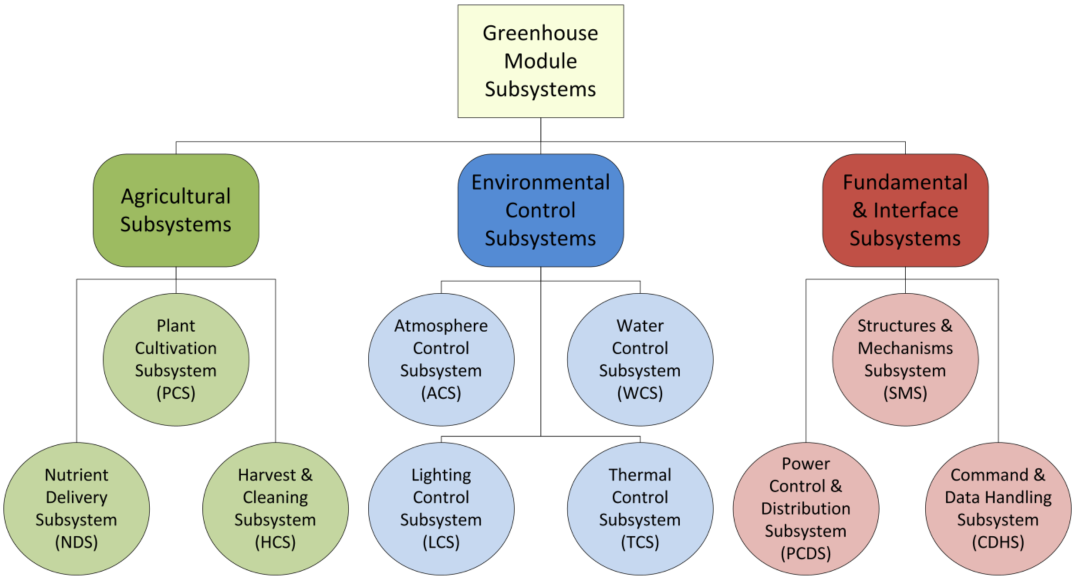


Figure 2-10: Classification of Greenhouse Module Subsystems

2.5.2 Fundamental & Interface Subsystems

The fundamental & interface subsystems are the framework of the greenhouse module. The Structures and Mechanisms Subsystem, the Power Control & Distribution Subsystem and the Command & Data Handling Subsystem are part of this subsystem category.

The functions of the *Structures & Mechanisms Subsystem* (SMS) of greenhouse modules and spacecraft are similar. According to reference [**14**], the SMS is the mechanical support of all other subsystems. The structures have to withstand all applied loads during the whole mission. In addition the radiation shielding is part of the SMS. Furthermore, the SMS is responsible for all mechanisms used in greenhouse modules.

Unlike the electrical power system (EPS) of spacecraft, the *Power Control & Distribution Subsystem* (PCDS) of greenhouse modules does not generate or store electrical power, it only controls and distributes the electrical power provided by the electrical power system of the habitat [**15**]. However, greenhouse modules can contain batteries or other power supply for cases of emergency. The power demand of greenhouse modules depends on the power consumption of the other subsystems. In general the Environmental Control Subsystems have the highest demands, especially the LCS. The PCDS has to supply each of the other subsystems with the voltage they need, to assure the subsystems can work as desired.

The *Command & Data Handling Subsystem* (CDHS) of greenhouse modules has to fulfill the same functions as in every spacecraft: receiving, validating, decoding and distributing of commands to other subsystems and gathering, processing and formatting of data as well as data storage. Security interfaces and computer health monitoring are also functions of the CDHS [**16**]. Due to maintain optimal growth conditions for plants in greenhouse modules the CDHS has to interpret the signals of several sensors to send suitable commands to each subsystem. The higher the level of automation of the greenhouse, the higher is the complexity of the CDHS. Furthermore, when the CDHS is a physical part of the greenhouse module, it has to be protected against the high humidity and temperature inside the greenhouse. The CDHS of greenhouse modules can also be part of the habitat CDHS.

2.5.3 Environmental Control Subsystems

The purpose of the environmental control subsystems is the maintenance of all environmental conditions, which are required either by humans or plants. Especially the optimal growth environment is necessary for the plants to achieve a high yield. Usually the subsystems of this group are combined in the ECLSS of the spacecraft, but it is suitable to split the functions into different subsystems when analyzing greenhouse modules. This subsystem group consists of the Atmosphere Control Subsystem, the Water Control Subsystem, the Lighting Control Subsystem and the Thermal Control Subsystem.

The *Atmosphere Control Subsystem* (ACS) is responsible for the air management of the greenhouse module. This responsibility covers the monitoring and control of the humidity, the composition and the pressure of the air. Furthermore, the ACS has to filter the air and has to assure, that the air circulates through the whole greenhouse module. Especially the humidity and the air composition have a great impact on the growth rate of plants. Usually, the ACS of greenhouse modules is connected to the ECLSS of the habitat to allow gas exchange.

The *Water Control Subsystem* (WCS) monitors and regulates the water distribution and water quality. The main task of the WCS is the delivery of the desired amount of water to every plant in the greenhouse module to achieve an optimal growth rate. The water quality is also important for the growth rate of plants. The WCS of greenhouse modules have a connection to the water management system of the habitat. However, the WCS must be capable to store a defined amount of water for cases of emergency.

The task of the *Lighting Control Subsystem* (LCS) is to provide and maintain the illumination of the greenhouse module. Therefore, it must be considered the lighting for the crew and the lighting for plants. The crew needs light for the work inside the greenhouse module, while plants need special lighting for an optimal growth rate. The growth rate depends on the light spectrum, the light intensity and the illumination phases. The required lighting conditions differ between plant species, consequently the LCS has to provide the optimal lighting conditions for each plant species for the maximum yield. When the greenhouse module uses the sun as a light source, the LCS has to regulate the irradiation of the sunlight.

In spacecraft, the *Thermal Control Subsystem* (TCS) maintains the temperature of all components at every time of the mission within their limits [**17**]. In general the TCS of greenhouse modules has to fulfill the same functions. In greenhouse modules the critical elements for the TCS are the plants. Different plant species have different requirements on the temperature; consequently, different temperature zones in the greenhouse module can exist and the TCS has to maintain the requirements of each zone. The thermal insulation of the greenhouse module is also part of this subsystem. The insulation has to ensure that the heat loss to the environment and to other parts of the habitat is as low as possible to reduce the energy demand of the TCS. However, depending on the lighting source, special cooling devices are necessary to protect the plants from overheating.

2.5.4 Agricultural Subsystems

Agricultural subsystems encompass all subsystems directly related to the plants. Parts of this subsystem group are the Plant Cultivation Subsystem, the Nutrient Delivery Subsystem and the Harvest & Cleaning Subsystem.

The *Plant Cultivation Subsystem* (PCS) supports the plants during all development stages. The PCS contains the growth medium for the plants, the plants themselves and can be divided into root and shoot zone. The design of the PCS is directly affected by the selected plant cultivation method and the used growth medium. Furthermore, the PCS has to ensure, that the plants have a solid stand in the growth medium and grow as desired. Generally, the plant cultivation system consists of several growth units, which are separated from each other and have their own environmental conditions and nutrient composition depending on the plant species and development stage.

The *Nutrient Delivery Subsystem* (NDS) is responsible for the mixture of the plants' nutrients. As every plant species has other requirements concerning the nutrients, a special nutrient mixing system is required. The nutrient solution has to be distributed to every plant in the greenhouse module in the desired amount and composition. The storage of nutrients is also part of the NDS. Furthermore, the nutrient production can be part of the NDS of greenhouse modules, but usually this task is fulfilled by the waste treatment system of the habitat.

The task of the *Harvest & Cleaning Subsystem* (HCS) is the provision of all tools and materials that are necessary for harvesting and cleaning the cultivated plants. Therefore, the HCS has to have a waste storage system to temporarily store the inedible parts of plants, before they are distributed to the waste treatment system of the habitat. The crop gathered from plants has to be packed after the harvesting and cleaning procedure. Consequently, the HCS has to provide the tools for the packaging. Afterwards the packed crop has to be stored.

2.6 Summary

Chapter 2 presents a brief overview over the required scientific background for the analysis and evaluation of greenhouse modules within planetary outposts. The challenges of the environmental conditions in free space, on Moon and on Mars are described.

Furthermore, the human requirements are discussed with respect to the required amount of food, water and oxygen. In addition the atmospheric pressure, composition and relative humidity required for long duration missions are explained.

The third subchapter discusses the different kinds of Environmental Control and Life Support Subsystems compared to the mission duration. Consequently, for long duration or even permanent missions to other planetary bodies of the solar system, greenhouse modules are a necessity.

A summary of past and present food provision systems shows the evolution of these systems over the last decades of spaceflight, from the Apollo program to the ISS.

In the fifth subchapter a classification of all greenhouse module subsystems is established. Therefore, each category and the related subsystems are described. In addition the functions and tasks associated with each subsystem are explained.

3 Development of an Analysis and Evaluation Strategy

This chapter starts with the explanation of the methodology of the developed analysis and evaluation strategy in the first subchapter. In the second subchapter the chosen analysis method, the Morphological Analysis (MA) is described, followed by the explanation of two suitable evaluation methods in the third subchapter. The fourth subchapter describes the analysis and evaluation factors considered during this thesis.

3.1 Methodology

The methodology of the proposed analysis and evaluation strategy consists of four steps:

- Data Acquisition,
- System Analysis,
- Evaluation and
- Discussion.

They are described in the following paragraphs. Each of these steps has subordinated tasks, as shown in Figure 3-1.

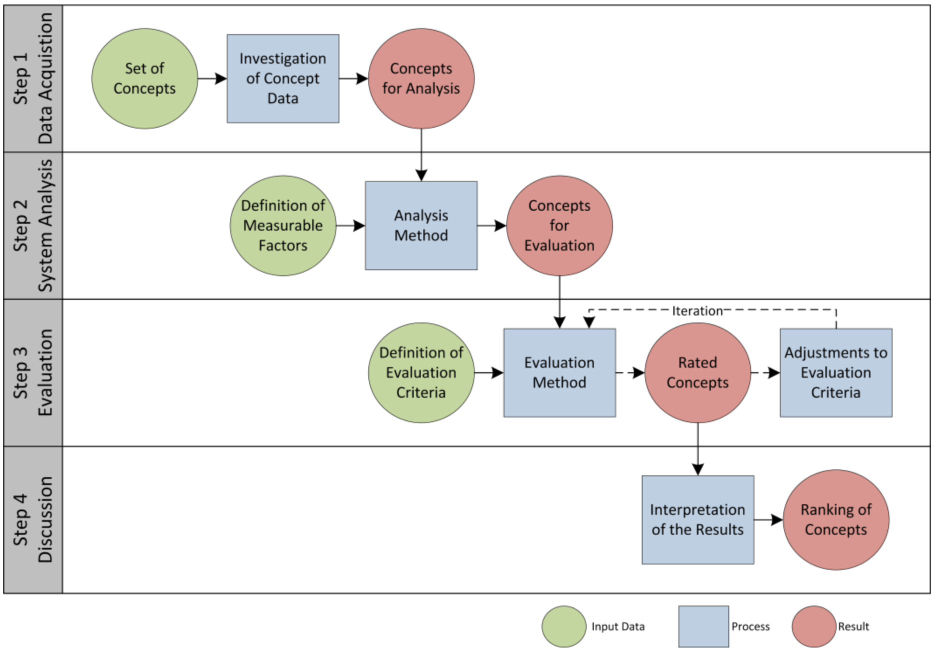


Figure 3-1: Methodology of the developed analysis and evaluation strategy

The first step, the *Data Acquisition*, starts with a set of concepts considered for the analysis and evaluation. After the definition of the set, data and information about the concepts have to be gathered and investigated. Depending on the quantity, quality and reliability of the data, it has to be considered which of the concepts are selected for the system analysis.

The *system analysis* is the second step, during which the results of the first step are analyzed with a suitable analysis method and defined analysis criteria. The definition of the analysis criteria depends on the goals of the analysis and evaluation strategy, and on the available data concerning the selected concepts. Potential analysis criteria are described in detail in Chapter 3.4. After the definition of the criteria, an analysis method has to be chosen. In this thesis the Morphological Analysis is selected for the system analysis. An explanation of the MA can be found in Chapter 3.2. The result of this step is a list of analyzed concepts.

At the beginning of the third step, the *evaluation*, the analyzed concepts of the previous step has to be split into different groups of concepts, depending on their purpose. Only concepts with the same purpose can be evaluated and compared to each other. To evaluate the concepts, evaluation criteria has to be defined. Usually, these criteria are a subset of the analysis criteria. Various evaluation methods exist and the analyst has to select an appropriate method. During this thesis the Equivalent System Mass (ESM) and the Analytical Hierarchy Process (AHP) are considered to be suitable for the evaluation of greenhouse module concepts. Both methods are described in Chapter 3.3. The output of the evaluation step is a list of rated concepts. However, when the result does not fit to the expected outcome or other reasons exist, the evaluation criteria and method can be adjusted. When adjustments are made, the evaluation has to be repeated.

In the fourth step, the *discussion*, the results of the analysis and evaluation have to be checked on their consistency and interpreted by the analyst. The outcome of this step of the strategy is a ranking of the investigated concepts.

3.2 Analysis Method – The Morphological Analysis

The Morphological Analysis was developed *"by Fritz Zwicky, the famous astrophysicist and jet engine pioneer, to describe a technique for identifying, indexing, counting, and parameterizing the collection of all possible devices to achieve a specified functional capability."* [**18**]

According to reference [**19**], the procedure of a MA consists of four phases:

Phase 1: Formulation of the problem,
Phase 2: Identification of all characteristic parameters,
Phase 3: Subdivision of each parameter into all possible options,
Phase 4: Analysis and evaluation of all possible parameter-option combinations.

In the first phase a precise *formulation of the problem* or the wanted functional capability has to be established.

In the second phase, the *identification of all characteristic parameters*, all parameters which affect the problem have to be identified.

During the third phase of the MA, the *subdivision of each parameter into all possible options*, the Morphological Box is constructed. The Morphological Box is the main tool of the MA and visualizes all parameters and their options in a table. The options have to be carefully selected, so that only one option per parameter is feasible at the same time. An exemplary box is shown in Table 3-1. A number of possible options n_m exist for each parameter m. The green highlighted options in Table 3-1 form one out of N possible configurations.

Usually the fourth phase, the *analysis and evaluation of all possible parameter-option combinations*, is done by a separate evaluation method. The number of combinations N for a given Morphological Box can be calculated by multiplying the number of options of each parameter. For the example in Table 3-1 the formula is:

$$N = n_A * n_B * n_C * \ldots * n_m \,. \tag{3}$$

Table 3-1: Exemplary Morphological Box with *m* Parameters and *n* Options

Option	Parameter $\boldsymbol{A}$	Parameter $\boldsymbol{B}$	Parameter $\boldsymbol{C}$	…	Parameter $\boldsymbol{m}$
1	$A-1$	$B-1$	$C-1$	…	$m-1$
2	$A-2$	$B-2$	$C-2$	…	$m-2$
3	$A-3$	$B-3$	$C-3$	…	$m-3$
⋮	⋮	⋮	⋮		⋮
$\boldsymbol{n}$	$A-n$	$B-n$	$C-n$	…	$m-n_m$
Exemplary configuration	$A-1$	$B-3$	$C-2$		

Reference [**20**] states, that the MA has the following advantages:

- Richness of data. MA can provide a multitude of combinations and permutations of a given problem.
- Systematic analysis. This technique allows a systematic analysis of current and future structures of a system.

3.3 Evaluation Methods

This subchapter describes the evaluation methods and concepts suitable for the evaluation of greenhouse modules. In Chapter 3.3.1 the Equivalent System Mass evaluation concept is explained, follow by the description of the Analytical Hierarchy Process in Chapter 3.3.2.

3.3.1 Equivalent System Mass

The Equivalent System Mass (ESM) is an evaluation concept for the ranking of trade study options. This method was developed by the National Aeronautics and Space Administration (NASA) for their Advanced Life Support (ALS) Program to find out which of several options has the lowest launch costs, depending on a set of parameter and properties.

According to reference [**21**], the ESM is used to calculate the transportation costs of an ALS system. All system parameter are converted to a mass equivalent, to avoid using currencies for comparisons, because transportation costs are proportional to the system mass. The calculated ESM value of a system represents the system mass and appropriate portions of supporting system mass. Pressurized volume, power generation, cooling and crewtime are typical supporting system factors.

The calculation of an ESM value consists of iteration with the following six steps [**21**]:

1. Determining of analysis objectives,
2. Determination of the mission of interest and related assumptions,
3. Determination of the system characteristics that should be captured in the analysis,
4. Definition of the system extent and level of detail,
5. Application of data,
6. Interpretation of the results.

During the first step, the *determination of analysis objectives*, the objectives of the ESM computation are defined to determine the mission of interest and system characteristics related to the trade study. Furthermore, the objectives have to be defined in an appropriate level of detail to avoid complications during the computation.

The second step, the *determination of the mission of interest and related assumptions*, is used to make assumptions about the operating environment, the subsystem of interest and the surrounding system. NASA defines several assumptions and missions of interest in two reports: the Advanced Life Support Systems Integration, Modeling, and Analysis Reference Missions Document (ALS RMD, [**22**]) and the Advanced Life Support Baseline Values and Assumptions Document (ALS BVAD, [**23**]).

According to reference [**21**], the *determination of the system characteristics that should be captured in the analysis* is the third step in the process of calculating an ESM value. During this step the analyst decides which characteristics are investigated during the trade study based upon the objectives. Characteristics might be excluded from the study due to a lack of data or other means. Usually, the characteristics are based upon the function, the availability, the gravity dependence, the noise levels, the safety, the radiation susceptibility or other parameters of the investigated system.

In the fourth step, the *definition of the system extent and level of detail*, the analyst has to define the investigated systems to a level of detail necessary for an appropriate comparison of the characteristics of interest between the systems. However, functional differences between the system options can complicate the identification of a suitable level of detail for the calculation of an ESM value.

The *application of data*, the sixth step, is necessary to adjust the data gathered from researchers, technology developers or scientific publications for the evaluation with the ESM method. Reference [**21**] states the development status adjustment and the system scaling as the most common types of data modification in an ESM analysis. However, data adjustments are not limited to both of these. To achieve a reliable result with an ESM evaluation, all study options have to be normalized to the same development state. Therefore, the analyst has to assume the future development and the essential parameters of a technology. Usually, data received from researchers and system developers has to be scaled to an appropriate size for the ESM study. The scaling factor commonly is a system specific parameter like the mass flow rate. After determining the scaling factor, all parameter values of the investigated system have to be adjusted. However, some systems can require more than one scaling factor.

The *interpretation of the results* is the final step in the ESM process. All results of the procedure have to be interpreted and described in an appropriate style concerning all assumptions made during the ESM calculation.

The ESM of a system is calculated as the sum of the ESM of each subsystem of the system of interest. The parameters required for the ESM equation:

$$\mathrm{ESM} = \sum_{i=1}^{n}\Big[\big(M_{I_i} * SF_{I_i}\big) + \big(V_{I_i} * V_{eq_i}\big) + \big(P_i * P_{eq_i}\big) + \big(C_i * C_{eq_i}\big) + \big(CT_i * D * CT_{eq_i}\big) + \big(M_{TD_i} * D * SF_{TD_i}\big) + \big(V_{TD_i} * D * V_{eq_i}\big)\Big], \quad (4)$$

are shown in Table 3-2.

The *initial mass* M_{I_i} consists of any mass in subsystem i, that is not time- or event-dependent and not part of the volume, power and cooling terms. The mass for the structure of pressurized volume, for the generation of power and for the provision of cooling is accounted in the associated terms. The *initial volume* V_{I_i} parameter pertains any pressurized volume required to house and access subsystem i. The parameter for the *required power* of subsystem i is P_i. The *cooling* term C_i pertains the heat rejection required for subsystem i. CT_i is the parameter for the *crewtime* required to operate and maintain subsystem i. The *time- or event-dependent mass* M_{TD_i} consists of any mass that is dependent on the mission duration and progress. Consumables, spare parts and process expendables are examples for this mass term. The *time- or event-dependent volume* V_{TD_i} is the required pressurized volume associated with M_{TD_i}. The *stowage factors* SF_{I_i} and SF_{TD_i} pertain all equipment required to secure the system, which can be racks, trays or other equipment. The *equivalency factors* V_{eq_i} , P_{eq_i}, C_{eq_i} and CT_{eq_i} are the ratio of the resource cost, in units of mass, to resource use. In the ALS BVAD document ([**23**]) numerical values and assumptions for the calculation of the stowage and equivalency factors can be found.

The reliability of an ESM analysis depends on the accuracy of the input data used for the calculation of the ESM value, as well as on the modification of the data. The ESM evaluation method is a cost metric. Therefore, the ESM is not capable of taking into account the reliability, safety and performance of the investigated systems. Furthermore, it is not feasible to evaluate qualitative properties of a system with the ESM equation. Consequently, reference [**21**] concludes that the ESM concept should not be the only evaluation method used to compare and evaluate trade study options.

Table 3-2: Explanation of ESM equation parameter [21**]**

Parameter	Unit	Name
ESM	kg	Equivalent System Mass value
M_{I_i}	kg	Initial mass of subsystem i
SF_{I_i}	kg/kg	Initial mass stowage factor for subsystem i
V_{I_i}	m^3	Initial volume of subsystem i
V_{eq_i}	kg/m^3	Mass equivalency factor for the pressurized volume support infrastructure of subsystem i
P_i	kW_e	Power requirement of subsystem i
P_{eq_i}	kg/kW_e	Mass equivalency factor for the power generation support infrastructure of subsystem i
C_i	kW_{th}	Cooling requirement of subsystem i
C_{eq_i}	kg/kW_{th}	Mass equivalency factor for the cooling infrastructure of subsystem i
CT_i	CM-h/y	Crewtime requirement of subsystem i
D	y	Duration of the mission segment of interest
CT_{eq_i}	kg/CM-h	Mass equivalency factor for the Crewtime of subsystem i
M_{TD_i}	kg/y	time- or event-dependent mass of subsystem i
SF_{TD_i}	kg/kg	time- or event-dependent mass stowage factor of subsystem i
V_{TD_i}	m^3	time- or event-dependent volume of subsystem i

3.3.2 Analytical Hierarchy Process

The Analytic Hierarchy Process (AHP) was developed by T. L. Saaty in the 1970s and is used in multiple criteria decision making problems. It involves the reduction of complex decisions to a series of pairwise comparisons. After synthesizing the results, decision-makers arrive at the best decision with a clear rationale for that decision.

According to reference [**24**], the AHP can be divided into six steps:

1. Illustration of the decision making problem,
2. Pairwise comparison of criteria,
3. Ranking of the criteria and alternatives,
4. Verification of the consistency of the evaluation,
5. Interpretation of the results,
6. Sensitivity analysis of the results.

In the first step, the *illustration of the decision making problem*, a hierarchy of criteria, subcriteria has to be developed by the decision analyst. Figure 3-2 shows an exemplary hierarchy for an AHP. At the top of the hierarchy stands the focus or goal of the decision making problem and at the bottom are all possible alternatives or solutions listed. Between the focus and the alternatives is the hierarchy of criteria and subcriteria, which affect the decision making process. The elements of the hierarchy have to be defined by the analyst. Therefore, three principles have to be considered [**24**]:

1. The elements of the same level of the hierarchy has to be independent to each other,
2. The number of elements on the same level is limited to nine, this makes the comparison of the elements easier,
3. The elements of the hierarchy should represent the complete decision making problem.

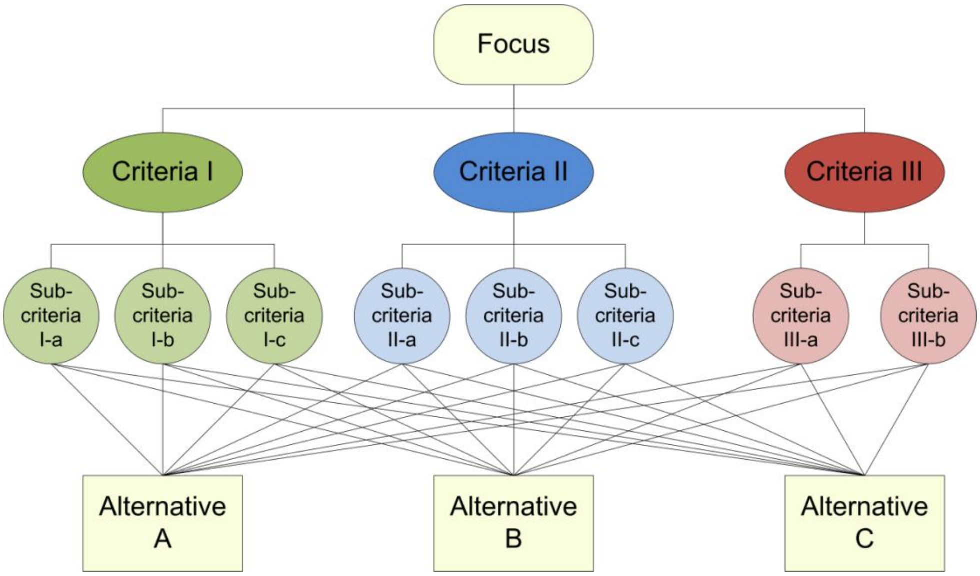


Figure 3-2: Example hierarchy for an AHP [25**]**

The second step, *the pairwise comparison of criteria*, is the key element of the AHP. The rating system shown in Table 3-3 is used to determine how important one element is over another element of the same level of the hierarchy. The system is a combination of a ratio scale from 1 to 9 and a semantic scale.

Table 3-3: The rating system for the pairwise comparison [25] [26]

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals	If activity *i* has one of the above numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	A reasonable assumption

The result of the pairwise comparison is a set of matrices, which represents the ratings of each comparison. For each level of the hierarchy a separate matrix is needed. This results in four matrices for the example shown in Figure 3-2, one to compare the criteria I, II and III and one for each set of subcriteria. Table 3-4 shows an exemplary comparison matrix with a_n elements, the values a_{ij} are the intensities of importance for each comparison.

Table 3-4: Comparison matrix with *n* elements [27]

$\boldsymbol{a_{ij}}$	$\boldsymbol{a_1}$	$\boldsymbol{a_2}$	…	$\boldsymbol{a_n}$
$\boldsymbol{a_1}$	$a_{11} = 1$	$a_{12} = 1/a_{21}$	…	$a_{1n} = 1/a_{n1}$
$\boldsymbol{a_2}$	a_{21}	1	…	$a_{2n} = 1/a_{n2}$
⋮	⋮	⋮	1	⋮
$\boldsymbol{a_n}$	a_{n1}	a_{n2}	…	$a_{nn} = 1$
$\boldsymbol{c_j}$	$c_1 = \sum_{i=1}^{n} a_{i1}$	$c_2 = \sum_{i=1}^{n} a_{i2}$	…	c_n

The third step of the AHP is the *ranking of the criteria and alternatives*. The ratings of the pairwise comparison are weighted to establish a ranking list of criteria and alternatives. In the AHP the weighted ratings are named priorities. The priorities are classified as local or global. Local priorities show the impact of elements of a lower level of the hierarchy with respect to the upper level. The local priorities are the basis for the global priorities. The global priority shows the impact of each element of one level of the hierarchy with respect to the focus of the decision making problem. The calculation of the ranking of criteria and alternatives is different for qualitative and quantitative criteria. Consequently, both calculations are described in the following paragraphs [**27**].

For qualitative criteria the calculation of the priorities w_i is based on reference [**27**] and starts by dividing each rating of the comparison matrix a_{ij} by the sum of its column c_j to achieve a normalized value. An exemplary normalized comparison matrix is shown in Table 3-5. Afterwards the sum of each row r_i of the normalized comparison matrix is divided by the number of elements in the row n. The result of this calculation is the local priority of each element with respect to the element of the upper level.

The calculation has to be executed with each comparison matrix of the decision making problem to achieve all local priorities. The global priority of a subcriterion can be calculated by multiplying his local priority with the local priority of the criterion in the upper level.

Table 3-5: Normalized comparison matrix with weighted scores *w* [27]

a_{ij}	a_1	a_2	...	a_n	r_i	w_i
a_1	a_{11}/c_1	a_{12}/c_2	...	a_{1n}/c_n	$r_1 = \sum_{j=1}^{n} a_{1j}/c_j$	$w_1 = r_1/n$
a_2	a_{21}/c_1	a_{22}/c_2	...	a_{2n}/c_n	$r_2 = \sum_{j=1}^{n} a_{2j}/c_j$	$w_2 = r_2/n$
⋮	⋮	⋮		⋮	⋮	⋮
a_n	a_{n1}/c_1	a_{n2}/c_2	...	a_{nn}/c_n	$r_n = \sum_{j=1}^{n} a_{nj}/c_j$	$w_n = r_n/n$
Σ	1	1	...	1		1

The calculation of the ranking of criteria and alternatives of quantitative criteria starts with the normalization of these values. Therefore, two formulas exist. When a high value is better for the focus of the analysis than a low one (e.g. a big area is better than a small one), the formula:

$$w_i = \frac{N_{a_i}}{\sum N_{a_n}} \tag{5}$$

has to be used for the normalization. Is a low value better than a high one (e.g. usually low costs are better than high ones), the formula:

$$w_i = \frac{1}{N_{a_i}} \Big/ \left(\frac{1}{N_{a_1}} + \frac{1}{N_{a_2}} + \cdots + \frac{1}{N_{a_n}} \right) \tag{6}$$

has to be used.

Table 3-6 shows an exemplary matrix for the calculation of local priorities of quantitative criteria [**27**].

Table 3-6: Weighted and overall alternative scores [27**]**

a_1	a_2	…	a_n	w_i				Σ
N_{a_1}	N_{a_2}	…	N_{a_n}	w_1	w_2	…	w_n	1

According to reference [**24**], during the fourth step, the *verification of the consistency of the evaluation*, the calculated scores of the previous step are checked on their consistency. Evaluations are consistent, when the requirements dominance, transitivity and invariance are met. The fulfillment of the dominance requirement is achieved, when the alternative with the best rank is presented as the solution of the decision making problem. The invariance cannot be verified in the AHP. Consequently, the verification of the consistency of the evaluation of the AHP contains the testing of the transitivity. The more elements are in the hierarchy, the more complicate is the fulfillment of the requirement.

The calculation of the inconsistency is based on the calculation of the eigenvalue of each element and is described in detail in reference [**27**]. However, a short description of the calculation procedure is described in the following. The first step is the calculation of the eigenvalue of each element. Therefore, the mean value $\bar{r_i}$ has to be calculated for each element. Afterwards, the mean value is used to determine the eigenvalues λ_i, see Table 3-7.

Table 3-7: Mean matrix and eigenvalue of each element [27**]**

a_{ij}	a_1	a_2	…	a_n	$\bar{r_i}$	λ_i
a_1	$w_1 * a_{11}$	$w_2 * a_{12}$	…	$w_n * a_{1n}$	$\bar{r_1} = \sum_{j=1}^{n} w_j * a_{1j}$	$\lambda_1 = \bar{r_1}/w_1 * a_{11}$
a_2	$w_1 * a_{21}$	$w_2 * a_{22}$	…	$w_n * a_{2n}$	$\bar{r_2} = \sum_{j=1}^{n} w_j * a_{2j}$	$\lambda_2 = \bar{r_2}/w_2 * a_{22}$
⋮	⋮	⋮		⋮	⋮	⋮
a_n	$w_1 * a_{n1}$	$w_2 * a_{n2}$	…	$w_n * a_{nn}$	$\bar{r_n} = \sum_{j=1}^{n} w_j * a_{nj}$	$\lambda_n = \bar{r_n}/w_n * a_{nn}$

A decision is consistent, when the maximum eigenvalue λ_{max} is equal to the number of elements n. When the maximum eigenvalue is greater than the number of element, inconsistency exists. The maximum eigenvalue is calculated with the formula:

$$\lambda_{max} = \frac{\sum_{i=1}^{n} \lambda_i}{n}. \tag{7}$$

The consistency index CI can be calculated out of the maximum eigenvalue and the number of elements:

$$CI = \frac{\lambda_{max} - n}{n-1}. \tag{8}$$

To judge whether a discrepancy can be tolerated, the consistency relationship CR is established as the division of the consistency index and the random consistency R:

$$CR = \frac{CI}{R}. \tag{9}$$

The random consistency is given as a function of the size of the matrix, see Table 3-8. Discrepancies can be tolerated, when $CR < 0{,}1$ is achieved. Is $CR > 0{,}1$, the evaluation and/or the hierarchy has to be reviewed.

Table 3-8: Random consistency R as a function of the size of the matrix [27]

Size of the matrix	1	2	3	4	5	6	7	8	9	10
Random consistency R	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

In the fifth step, the *interpretation of the results*, it has to be considered, that the AHP is a subjective decision making tool. The pairwise comparison is based on individual experiences and knowledge, the layout of the hierarchy also has a big impact on the results of the AHP. The interpretation itself can be done by several types of diagrams, graphs and tables.

Reference [**24**] describes the *sensitivity analysis of the results* as the sixth step in the AHP. The sensitivity analysis examines the impacts of changes in the weighting of criteria on the ranking of the alternatives. Due to continuous changing of the weight of each criteria, borders are determined, at which the ranking of the alternatives changes. The results of the AHP are steady, when small changes in the weights do not affect the ranking. The values of the pairwise comparison have to be reconsidered, when the results are unsteady.

The AHP is an effective evaluation method for the quantitative examination of unstructured problems, also with the integration of quantitative values. Furthermore, the AHP is a flexible tool which allows individuals and groups to define problems according to their approvals and receive a subjectively preferred solution. The incorporation of expert knowledge can lead to objectivation of the subjective solution. In addition, the AHP permits the revision of the stability and consistency of the solution [**27**].

Reference [**27**] summarizes the advantages of the AHP as followed:

- *Unity:* The AHP is single, easy to understand and flexible model for the analysis of unstructured problems.
- *Complexity:* The AHP combines deductive and system approaches for the analysis of complex problems.
- *Interdependency:* The AHP can handle interdependencies of system elements and can break existing paradigm.
- *Hierarchy Structure:* The AHP incorporates the natural cognitive tendency to order elements in categories and to group similar elements on the same hierarchy level.
- *Measurement:* The AHP provides a scale to measure immaterial criteria and a method for the determination of priorities.
- *Consistency:* The AHP incorporates the logical consistency of evaluations, which are used for the determination of priorities.
- *Synthesis:* The AHP provides a general approximation of the desirability of each alternative.

- *Compromises:* The AHP incorporates the relative importance of system parameters and therefore, allows the selection of that alternative, which is most suitable for the goals of the decision analyst.
- *Interpretation and Consensus:* During an AHP is no necessity to achieve a consensus, but rather the AHP achieves a representative solution out of a sequence of evaluations.
- *Repeatability:* The AHP allows the decision analyst to improve the problem definition, the problem evaluation and the problem comprehension through repetitions.

3.4 Definition of Analysis and Evaluation Factors

3.4.1 Factor Categorization

The factor categorization is based on the definition of greenhouse module subsystems established in Chapter 2.5. Consequently, each criterion is part of one of the four categories: Agricultural Factors, Environmental Factors, Fundamental Factors or Interface Factors. Despite the combination of Fundamental & Interface Subsystems to one group in the subsystem categorization, the related analysis and evaluation factors are split into two separate groups. Furthermore, the factors of each category are divided into qualitative and quantitative factors. For latter, suitable units based on the International System of Units (SI) are established. The values of the quantitative factors of the investigated concepts have to be converted into SI units to improve the comparability. For quantitative factors all possible options are described, whether they are reasonable or not. The following subchapters, one per category, describe each criterion in detail.

3.4.2 Fundamental Factors

3.4.2.1 Definition

Fundamental factors are established to analyze and evaluate the different aspects of the structures & mechanisms subsystem, the power distribution subsystem and the command & data handling subsystem. Eight fundamental factors are considered for the use in the analysis and evaluation of greenhouse module concepts, six qualitative and two quantitative factors. The Structures & Mechanisms Subsystem (SMS) is analyzed and evaluated by the factors module shape, arrangement of growth area, distribution of aisles, module structure, adaptability of internal configuration, level of automation, specific cultivation volume and complexity. There are no factors for the analysis and evaluation of the Power Distribution and Control Subsystem (PCDS) in this category, because the factors concerning the PCDS are part of the interface factors category. During this thesis no factors related to the Command & Data Handling Subsystem (CDHS) are investigated, because the design of the CDHS is generally the same for each greenhouse module. Table 3-9 shows the summary of all fundamental factors separated into qualitative and quantitative factors.

Table 3-9: List of Fundamental Factors

Qualitative Factors	Quantitative Factors
Module Shape	Module Mass
Arrangement of Growth Area	Dimensions
Distribution of Aisles	Specific Cultivation Volume
Module Structure	Complexity
Adaptability of Internal Configuration	
Level of Automation	

3.4.2.2 Module Shape

Greenhouse modules can have various shapes. The module shape affects the arrangement of the growth area, the overall growth area and the ratios growth area and growth volume per total volume. Furthermore, the module mass significantly depends on the shape. Feasible are:

- prismatic,
- hemispherical,
- spherical or
- irregular

shapes.

Prismatic modules are typically chosen, when the modules are fully integrated on Earth and launched with rockets. However, the size of prismatic modules integrated on Earth is restricted to the size of launcher fairings. The base of prisms can be elliptical, polygonal, hemispherical or circular. Today's modules for space stations are usually prisms with a circular base, also named cylinders. This results from the aerodynamic cylindrical shape of rockets in which cylindrical modules have the highest volume efficiency. Due to the experience gained during the design and construction of space stations in the last decades, prisms and especially cylindrical ones are a well-known design. Consequently, the development and construction costs for these types are relatively low compared to other shapes.

A *hemispherical*, or dome like design can be used to cover a big area while keeping the mass of the construction low. Therefore, a framework of lightweight materials is covered with a Kevlar based shell. Usually, hemispherical modules are launched as individual components and have to be assembled at the destination. Consequently, dome greenhouses are only suitable when a growth area of several hundred square meters is required to feed the crew.

A *spherical* shape is another option for the design of greenhouse modules. A concept for a module with a spherical shape was investigated by NASAs Johnson Space Center in 1989 to be installed at Lacus Veris on Moon [**28**]. Thereby, an inflatable outer shell was proposed to form the sphere. The sphere himself was buried half into the lunar, while the upper half was covered with regolith-filled tubes to protect the crew against radiation. A similar module could be used as a greenhouse with several floors. An inflatable sphere is light weight and therefore, can reduce the launch and transportation costs. However, the sphere has to be enfolded and anchored at the destination which requires a digging device. Furthermore, the sphere has to be outfitted with the required systems at the destination which causes a high work load on the crew.

Irregular shapes are theoretically feasible, but until now no concept for a greenhouse module with an irregular shape exists. However, each design with an irregular shape has to be investigated in detail on the usefulness for greenhouse modules. When the benefits of the irregular shape exceed that of regular shapes, it can be considered for greenhouse designs.

3.4.2.3 Arrangement of Growth Area

The arrangement of growth area inside greenhouse modules is an important factor for maximizing the yield, because the internal configuration defines the ratios growth area and growth volume per total volume. The maximum growth height is also affected by the arrangement of growth area. There are several ways to arrange the cultivation area inside greenhouse modules:

- plain growth area,
- growth area allocated on shelves,
- conveyor like growth area or
- rotating cylinder.

The simplest type of arrangement is a *plain* growth area, which is similar to the field agriculture on Earth. The volume efficiency of this arrangement is low, because the growth height of most of the food plants is lower than one meter. Therefore, a field like growth area is less suitable for extraterrestrial greenhouse modules. A plain growth area is only applicable for tall growing plants like trees or bushes, but these plants are less considered for the use in space until now.

Shelf configurations are stacked plain growth areas. Consequently, the ratio of growth volume per total volume is significantly higher compared to plain growth area configurations. The height of the different levels of the shelf can vary, so that plants with different growth heights can be cultivated. Usually, each level of the shelf has its own environmental control system which provides light, water, air and nutrients to the plants. It is also feasible to divide each level of the shelf into separated sections, which could be useful to separate different plant species from each other.

The levels of shelves can be integrated horizontally or angled. A horizontal shelf, see Figure 3-3, provides the same growth height to all plants on it. When a change in available growth height is needed, the whole level has to be moved into another position, or all plants on the level have to be switched into another level with an appropriate height. Angled shelves solve this problem due to their sloped levels. In angled shelves, see Figure 3-4, the plants start as seedling at the narrow end of the level. While the plants grow they were moved by hand or automatically to the broad end of the level. The angle and the growth height is designed in a way, that the plants are matured and ready for harvesting when reaching the broad end of the level. Once the angle and growth height of a level is adjusted to the plant species it produces a continuous food output without reconfiguration. Consequently, the work load for angled shelves is lower compared to horizontal shelves.

The width of all shelf constructions is restricted to the nominal arm length of crew members to assure an ergonomic acceptable work. When the shelves are wider than the nominal length of an arm, some kind of drawers are required. However, drawers need free space to be pulled out of the shelf. Consequently, the width of shelves with drawers depends on the aisle width.

Figure 3-3: Growth area arrangement - Horizontal shelves

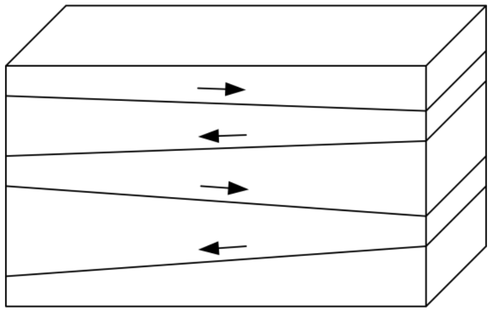


Figure 3-4: Growth area arrangement - Angled shelves

The *conveyor* type growth area arrangement is a development of the Institute for Biomedical Problems of the Russian Academy of Sciences. The archetypes of this growth area arrangement are the conveyors which led to the rise in productivity of assembling units in the machinery industry. In greenhouses with conveyor type arrangement of growth area plants are located on the conveyor and forwarded during their growing stages. The growth area is arranged in a spiral cylinder with a conveyor located on the axis. The cultivated plants start as seedlings in the lowest part of the construction and are conveyed to the highest part during their growth.

The dimensions of the spiral are a function of the crop growth curve. Consequently, each plant species need a unique spiral cylinder. Figure 3-5 shows the cross section of spiral cylinder designs for cabbage, carrot, tomato and pepper. The plants themselves are grouped on root modules. The plants of one root module are planted and harvested at the same time. The advantage of conveyor type growth areas is the up to 30 % increase in yield compared to a plain growth area with the same lighting input and size. The higher efficiency is the result of better light concentration towards the convex growth area and the widening of the space between the leaves of different plants. In addition to the higher yield, the nearly double reduction of required volume compared to a plain growth area. Planting and harvesting is always performed at the same position which reduces the crew time required for these actions and allows automation. However, the conveyor which carries the plants increases the complexity of the greenhouse module [**29**].

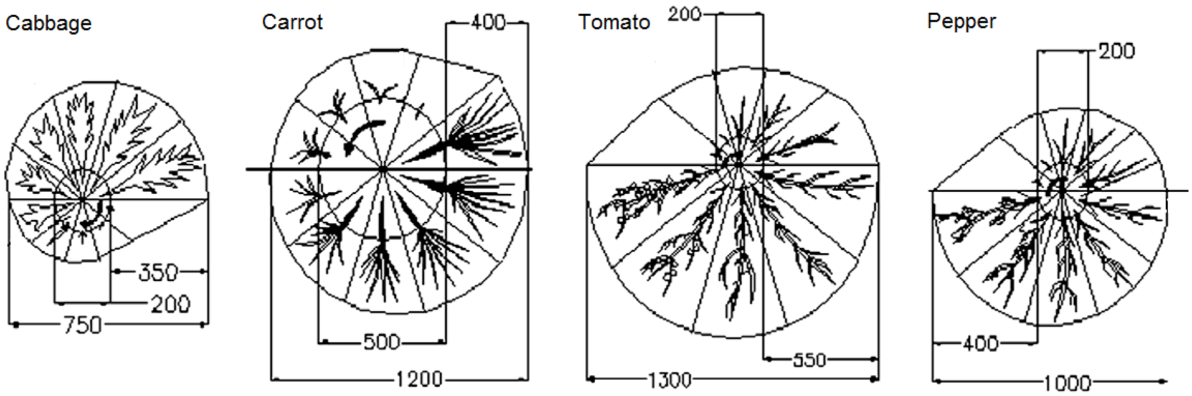


Figure 3-5: Conveyor type growth area for different plants, adapted from [29**]**

The *rotating cylinder* arrangement was developed by the Canadian company Omega Garden International. As shown in Figure 3-6, the plants are cultivated on the inner wall of the cylinder, while the light source is located on the rotation axis of the cylinder. Consequently, all plants have the same distance from the lamps. While the cylinder is rotating, the root medium of the plants is dipped into a water-nutrient mixture when reaching the reservoir at the bottom. This arrangement type is volume efficient and furthermore, the rotation has a positive effect on the yield. The plants have to counter different gravity vectors during the rotation which leads to bigger and stronger plants. In addition, the plants' growth rates are higher than without rotation [**30**]. However, the low gravity on Moon and Mars would reduce these benefits. The disadvantage of the rotation cylinders is their relatively inflexibility, because plants with different growth heights need uniquely scaled cylinders. Furthermore, the concave shape of the growth area leads to reduced space for the top leaves of the plants which reduces the photosynthetic efficiency.

Figure 3-6: The Volksgarden concept of Omega Garden International [30**]**

3.4.2.4 Distribution of Aisles

The consideration of the aisle distribution is primarily required for shelves as accommodation for the growth area. The width of the aisles has to be considered on ergonomic and clearance reasons. They have to provide enough room for the crew to do their work in a proper way. However, the more room is used for aisles, the smaller is the overall growth area. Consequently, the size and distribution of aisles is a compromise between ergonomics and maximization of growth area. All in the following discussed distributions are commonly used for prismatic module shapes, whereby the prisms base can have every shape discussed in Chapter 3.4.2.2. To simplify matters, the following figures show the cross section of a prism with a rectangular base. The following configurations are considered for the use in prismatic greenhouse module designs:

- center aisle two shelves,
- two aisles center shelf,
- two aisles three shelves or
- flexible aisle moveable shelves.

In the *center aisle two shelves* configuration the shelves are located at the walls of the module while the aisle is centered between them, see Figure 3-7. This configuration is not suitable when the module is docked only at one side to the habitat, due to emergency reasons.

When the sole aisle is blocked, crew members can be trapped inside the module and cannot escape. Furthermore, when this aisle distribution is under investigation for cylindrical modules, it has to be considered that the volume and area for plant growing in the shelves is relatively low due to the curved shaped.

The configuration *two aisles center shelf* has a large centered shelf and two aisles, one at each side of the shelf, shown in Figure 3-8. All cables and pipes are located in the center of the module which is advantageous for this configuration, because no extra space is required to deliver energy, water, air and nutrients to separated shelves. However, this configuration is not suitable for cylindrical modules, in which the aisle would be too small due to the curved shape of the module structure.

A configuration with *two aisles* and *three shelves* is a combination of the two previous described aisle distributions. The two outer shelves are smaller compared to the center shelf. In case of emergency, the two aisles assure a way out for the working crew member inside the greenhouse module. Due to the restrictions for the width of aisles and shelves explained earlier, a configuration with outer shelves and two or more aisles is required for large greenhouse modules. Reference [**31**] propose such a configuration of four shelves and three aisles for the Lunar FARM concept described in Chapter 4.1.3. The developer of the BIO-Plex facility at NASAs Johnson Space Center selected the two aisles three shelves configuration for their Biomass Production Chamber [**32**].

The *flexible aisle moveable shelves* configuration is an adaption of a shelf design often found in libraries and archives. Thereby, all shelves are moveable on rails and only one aisle exists. The shelves can be moved by hand or motor-driven. Consequently, the position of the aisle is flexible and depends on the position of the shelves. Originally, this configuration was designed to save space and therefore to achieve a higher packing density compared to normal shelf configurations with aisles on each side of the shelves. The flexible aisle moveable shelves configuration used in greenhouses has a high ratio of growth volume to total volume, because only one aisle is required and therefore more space for the cultivation of plants is available. However, the connection of moveable shelves to the electrical power, water, nutrients and air distribution systems is complicated and increases the complexity of the configuration. Nevertheless, the higher growth area compared to other configurations of the same size can exceed the increase in complexity and mechanisms, especially in large greenhouse modules.

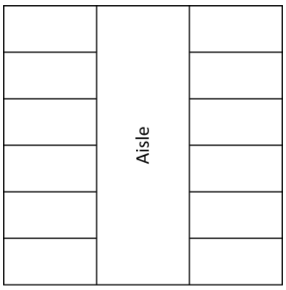


Figure 3-7: Center aisle two shelves configuration, derived from [32**]**

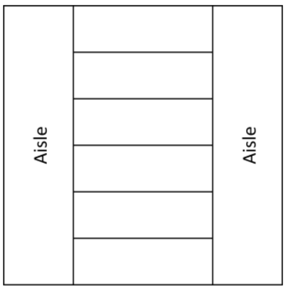


Figure 3-8: Two aisles center shelf configuration, derived from [32**]**

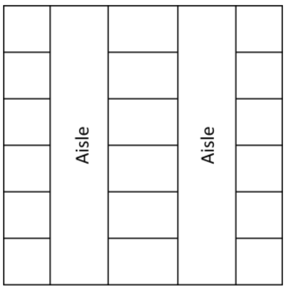


Figure 3-9: Two aisles three shelves configuration, derived from [32**]**

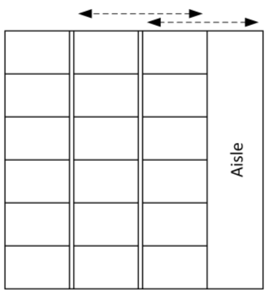


Figure 3-10: Side aisle moveable shelves configuration, derived from [32**]**

3.4.2.5 Module Structure

The module structure affects several other parameters, but mainly the mass and complexity. Table 3-10 shows the estimated total mass of different types of module structure for an internal volume of 655 m^3. The structure of greenhouse modules can be:

- rigid,
- semi-deployable,
- fully deployable or
- made out of in situ materials.

Rigid structural designs are the common way for the construction of crewed modules. According to reference [**31**], the advantages of rigid structures are the confidence in the technology and the pre-installation and verification of all equipment before launch. In addition a first set of plants can be planted and grown during the transfer to assure a continuous harvesting cycle from the arrival at the destination. However, rigid structures have to be strong enough to withstand the loads during launch from Earth. Therefore, the mass of rigid structures is significantly higher than for other structural designs. Reference [**31**] estimates the mass of a rigid greenhouse module with a length of 12 meters, a diameter of 8 meters and an internal volume of 655 cubic meters to around 8000 kg. Furthermore, the dimensions of rigid structures are defined by the fairings of available launch systems.

Semi-deployable or hybrid designs of greenhouses has a rigid structural compartment and attached deployable sections. Hybrid designs combine the advantages of rigid and deployable structures with a moderate mass. The mass and volume of semi-deployable designs are less than for rigid ones, while it is still possible to preinstall systems and plants. The deploying mechanisms increase the complexity. In addition, the interface between the rigid and the deployable sections increase the complexity even more and are weak spots for leakages. Consequently, the complexity of hybrid designs exceeds that of fully deployable systems. However, a semi-deployable greenhouse module with dimensions of 12 meters length, 8 meters diameter and an internal volume of 655 cubic meters would have a mass around 5500 kg [**31**].

Fully *deployable* or inflatable structures are currently under investigation by all space agencies and some companies. Modules with deployable structures usually are packed to a relatively small volume and unfolded at the target location, which reduces the mass of the module, but increases the complexity due to the required deploying mechanisms. Reference [**31**] estimates the mass of a fully deployable greenhouse module with a length of 14 meters, a diameter of 8 meters and an internal volume of 655 cubic meters to around 1200 kg. Inflatable structures usually have a shell out of Kevlar combined with other elastic polymeric materials. The materials make the shell flexible, light weight and strong enough to withstand the environmental conditions [**31**]. In fully deployable modules plants cannot be planted until the structure is completely enfolded, which is disadvantageous, because deployable greenhouses need a setup time before the first plants can be harvested. The nutrition of the crew for this timespan has to be covered with stored food.

Table 3-10: Estimated mass for different structural types for a volume of 655 m^3, derived from [31]

Rigid	8000 kg
Semi-deployable	5500 kg
Deployable	1200 kg

The usage of *in situ materials* is also possible to build greenhouse modules on other planetary bodies. Thereby, the materials can be applied on pre-fabricated structures to shield the crew against radiation or the materials are used to create construction components for the greenhouse. In addition, the local terrain, like caves, tunnels, lava tubes, mountains and craters himself can be used as structures. Therefore, a pressurized environment is created by sealing the existing terrain formations against the environment to provide a suitable atmosphere for plants and humans. Module structures which use or are out of in situ materials would reduce the launch mass of greenhouse modules significantly. Consequently, the costs for these modules are lower than for pre-fabricated modules. However, further research in the usage of in situ materials is required before greenhouse modules build out of them are feasible [**28**].

3.4.2.6 Adaptability of Internal Configuration

The internal configuration has to support the plants during all growth stages. To maximize the yield of the cultivated plants, the internal configuration has to be adapted while the plant is growing. Furthermore, it is essential that the configuration is somehow adaptable to different plant species. Especially, the adaptableness of the growth height is necessary to assure a customizable internal configuration. The internal configuration of greenhouses can be classified as:

- inflexible,
- semi-flexible or
- flexible.

Inflexible internal configuration cannot be adapted once they are assembled. Consequently, the grow height is given through the design of the greenhouse's internal configuration. This type of internal configuration does not increase the complexity of the module, but the achievable yield is lower compared to semi-flexible and flexible configurations.

In s*emi-flexible* designs the crew can adjust some parameters of the internal configuration during the mission to change the plant configuration. Furthermore, semi-flexible designs provide some options to react on unscheduled events. Depending on the mechanisms used for the adaptableness, the complexity of the greenhouse module can increase.

Flexible internal configurations are fully adaptable to a broad spectrum of parameter settings, which increases the amount of required mechanisms and systems significantly. However, the increase in yield and the ability to change the plant configuration in every way can legitimate the higher complexity of the greenhouse module.

3.4.2.7 Level of Automation

Automation of processes inside greenhouse modules is important to reduce the crew time required to plant, cultivate and harvest plants. Crew time is valuable during space missions, see Chapter 3.4.5.10, and all systems which can reduce the work load of the crew have to be investigated on their applicability [**33**]. Nevertheless, a higher level of automation would increase the complexity of greenhouse modules. Furthermore, the direct interaction with plants can satisfy psychological needs of the crew, see Chapter 3.4.5.11., subsequently the level of automation of greenhouse modules has to be considered wisely.

Depending on the integrated systems, greenhouse modules can have:

- none,
- partial or
- full

automation.

In greenhouses *without* any automation processes like planting, harvesting, nutrient mixing, and monitoring are performed by crew members, which generates high work load. The complexity of greenhouse modules without any automation systems would be very low compared to the other types of automation. However, such greenhouse modules are not suitable for planetary habitats, in which the crew size and consequently the available work power are restricted.

Partial automation is common in today's greenhouse module concepts. Thereby, some tasks are fulfilled by computers and control algorithms. The automatically control of temperature, lighting, humidity, ventilation, nutrient mixture and water supply is well known and was tested in several terrestrial testbeds. A partial automation should be the least level of automation for greenhouse modules proposed for future planetary habitats.

Fully automated greenhouse modules cover all tasks required to maintain the food production at the predicted level. Besides the monitoring and controlling of environmental and metabolic conditions, fully automated greenhouses have the ability to plant and harvest the cultivated plants without the help of crewmembers. Consequently, the work load on the crew is limited to monitoring and programming the automation processes. However, greenhouse modules with full automation have a high complexity compared to the other two types.

3.4.2.8 Module Mass, Dimensions and Volumes

The *module mass* directly affects the costs of greenhouse modules. Especially, the launch and transfer costs depend on the mass of the modules. The heavier the module, the higher are the costs. Furthermore, the overall mass per module should not exceed the launch capacity of available launch systems. The proposed unit for the module mass is kilogram, kg.

The *module dimensions* are required for the calculation of overall and pressurized volume. Typical dimensions are length, height, width and diameter. Dimensions are commonly measured in meter, m.

For the analysis of the volume of greenhouse modules total volume, pressurized volume and the ratio of growth volume per total volume have to be considered. The *total volume* is calculated by the outer dimensions of the module and is mainly required for the selection of the launch system and fairing. The *pressurized volume* is any volume that contains an atmospheric pressure suitable for humans and/or plants. The factor *specific cultivation volume* is established to evaluate the efficient use of volume. Growth volume is the volume which can be used for plant cultivation. It is calculated by the multiplication of the growth area in square meters with the appropriate maximum growth height in meters. The higher the ratio of cultivation volume per total volume, the higher is the efficient use of volume. All volumes are reported in cubic meters, m^3.

3.4.2.9 Complexity

The *complexity* of greenhouse modules depends on the number of different elements, on the amount of interconnections between the elements, on the functionality of the interconnections, and on the time dependency of the elements. The more elements are implemented in the greenhouse, the more interconnections are between these elements. Furthermore, the higher the time dependency of these elements, the higher is the complexity of the greenhouse module.

A highly complex system has a greater potential for failures compared to systems with a lower complexity. However, a higher complexity often results in reduced work load for the crew and in higher yields. Therefore, the performance of greenhouse modules with a high level of complexity can exceed those of low complexity and can be applicable for the use in planetary habitats. Nevertheless, the complexity of systems cannot be measured as a pure value. Consequently, the analysis of a greenhouses complexity is generally subjective. During this thesis the complexity of greenhouse concepts is evaluated by comparing the concepts to each other.

3.4.3 Environmental Factors

3.4.3.1 Definition

The defined set of environmental factors encompasses all analysis and evaluation factors related to the environmental control subsystems described in Chapter 2.5. Therefore, the environmental factors concern the atmosphere control subsystem, the water control subsystem, the lighting control subsystem and the thermal control subsystem. There were ten environmental factors identified during this thesis, five qualitative and five quantitative. The Air Control Subsystem (ACS) is analyzed and evaluated with the factors atmospheric composition, trace gas treatment, humidity, atmospheric pressure and the concentrations of carbon dioxide and oxygen. There are no environmental factors defined for the analysis of the Water Control Subsystem (WCS) during this thesis, because the design of this system is nearly the same in every greenhouse module. However, some factors related to the WCS are part of the interface factors category, because they describe the interface of the WCS with the habitat. For the evaluation of the Lighting Control Subsystem (LCS) the factors lighting type, lighting strategy and photosynthetic period are established. The type of temperature control and the air temperature are used to analyze and evaluate the TCS of greenhouse modules. Table 3-11 shows a summary of all environmental factors split into two columns, one for qualitative factors and one for quantitative factors.

Table 3-11: List of Environmental Factors

Qualitative Factors	Quantitative Factors
Lighting Type	Photosynthetic Period
Lighting Strategy	Humidity
Atmospheric Composition	Air Temperature
Trace Gas Treatment	Atmospheric Pressure
Temperature Control	Carbon Dioxide and Oxygen Partial Pressure

3.4.3.2 Lighting Type

The lighting system provides radiation, the sole source of energy for plants to grow and develop. In this thesis the word "light" is used for the photosynthetically active radiation (PAR) and not for the radiation that is visible to the human eye. PAR is defined as the radiation with wavelengths useful for photosynthesis of plants. The human eye can respond to wavelengths from 380 to 720 nanometers, while the wavelength of PAR is between 400 and 700 nanometers. However, sometimes the range is from 350 to 850 nanometers [**34**].

The sources of light can be broadly divided into:

- electrical,
- hybrid or
- natural lighting.

Electrical lighting includes all sources which are electrically powered and convert electricity to radiation. The sole source of radiation in natural lighting systems is the sun. Hybrid lighting systems combine natural and electrical sources of radiation.

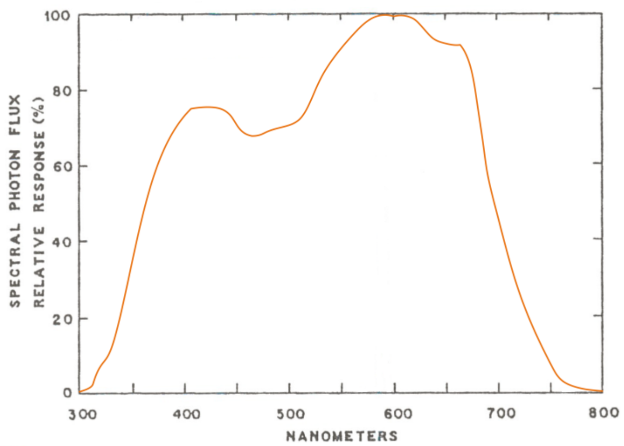


Figure 3-11: Spectrum of the Photosynthetic Active Radiation (PAR) [34]

Electrical Lighting

High-intensity discharge (HID) lamps excite gas atoms with an arc to emit radiation. The wavelength of the radiation depends on the excited gas. The irradiance of HID lamps is high compared to fluorescent and incandescent lamps, but it is difficult to provide a uniform radiation distribution, because HID lamps are point sources. Consequently, the radiation has to be distributed with reflectors over the whole growth area. There are three types of HID lamps for the provision of radiation to plants: high-pressure sodium lamps, metal halide lamps and mercury lamps [**34**].

High-pressure sodium (HPS) lamps produce radiation through exciting of highly concentrated sodium vapor and a small amount of mercury with an electrically powered arc. The spectrum of the emitted radiation is mainly between 550 and 650 nanometers, but low emission between 400 and 500 nanometers is also produced, see Figure 3-12. Hence, there is low emission in blue wavelengths. Therefore, lamps with higher irradiance in the blue spectrum have to be added to the lighting systems to provide this spectrum to the plants. HPS lamps have a high PAR efficiency compared to fluorescent, incandescence and other HID lamps. In addition, the lifetime of HPS lamps is high and their intensity is reduced slowly as the lamp ages [**34**].

Metal halide (MH) lamps excite vapors of metal halides (iodides of thorium, thallium, of sodium) and small portions of mercury to produce radiation. The wavelengths of the emitted photons depend on the gas inside the tube of the MH lamps. The main radiation output of MH lamps is between 400 and 700 nanometers. The spectrum of a MH lamp compared to PAR is shown in Figure 3-13. The disadvantages of MH lamps are the differences in spectral distribution of different lamps and the spectral shift when the lamps age. The PAR efficiency of MH lamps is slightly lower than that of HPS lamps. The average lifetime of MH lamps ranges from 12000 hours for 1000 W lamps to 20000 hours for 400 W lamps. The intensity of MH lamps decreases rapidly over time. After half of the lifetime the intensity is only 75 % of new lamps [**34**].

In *mercury lamps* vapor of mercury is excited by an electrical arc. The emitted photons have a bluish spectrum. Mercury lamps have a long average lifetime of 24000 hours, but after half of the lifetime, the output is only 70 to 85 % compared to new lamps. The biggest disadvantage of mercury lamps is the significantly low PAR efficiency. Unless UV or blue wavelengths are required, mercury lamps are less recommended for the lighting of plants [**34**].

Fluorescent lamps are long glass tubes filled with mercury vapor under low pressure and an inert gas, usually argon. At each end of the glass tube is an electrode. When a proper voltage is applied on the electrodes, an electric arc between them is generated. The arc excites the mercury ions and when they fall back to the ground state, radiation mainly at a wavelength of 253.7 nanometers is emitted. Photons with this wavelength are not suitable for plants. Therefore, the inner wall of the glass tube is coated with fluorescent powder, usually phosphor. The phosphor is activated by the incoming photons and emits new photons primarily at longer wavelengths suitable for plant growing. The spectrum of fluorescent lamps depends on the used phosphor mixture for the coating; the spectrum of a cool white fluorescent lamp is shown in Figure 3-14. Fluorescent lamps provide a continuous and uniformly distributed radiation when placed closed together. The PAR efficiency of fluorescent lamps is generally high, but is affected by the ambient temperature. The maximum output of fluorescent lamps is at a temperature of 38°C. Therefore, the ambient temperature has to be slightly below 38°C to provide the maximum output. However, the low operating temperature reduces the heat input into the growing area. During the operation the coating of the electrodes is evaporated, mainly during the start-up. Consequently, the frequency of turning the lamps on and off affects the lifetime. During the first 100 hours of operation, the output of fluorescent lamps decreases rapidly. After this period the degradation is more continuous, leading to 70 % or less after 6000 hours [**34**].

Incandescent Lamps utilize heated bodies to emit light. The light of incandescent lamps is blackbody radiation. Consequently, the wavelengths of the photons depend on the temperature of the heated element. To create light useable by plants a temperature above 2600°K is required. In commercial incandescent lamps filaments made of tungsten are heated with electricity to a temperature between 2770 and 3050°K. The higher the voltage, the higher the temperature raises. The spectrum of the emitted photons has a large component of wavelengths in the infrared spectral band. Figure 3-15 shows the comparison of the spectrum of an incandescent lamp and PAR. Hence, most of the electrical energy used by incandescent lamps is converted to heat, therefore, the efficiency of these lamps is low and not competitive to over lamp types. In addition, the heat generated by of incandescent lamps has to be removed out of the growth area to avoid damaging of the plants. The lifetime of commercially available incandescent lamps ranges from 700 to 1000 hours and the output at the end of life is about 85 % of the original. The very low lifetime and efficiency compared to other lamp types leads to the conclusion that incandescent lamps are not recommended for the use in lighting systems [**34**].

Low-pressure sodium (LPS) lamps are similar to HPS lamps. Contrary to HPS lamps, the pressure in LPS lamps is lower and no mercury vapor is present. Thus, only the excited sodium provides the radiation output of LPS lamps. The spectrum of the radiation is limited to wavelengths around 589 nanometers, see Figure 3-16. The output of LPS lamps is not high enough to provide sufficient lighting for plants. Therefore, LPS lamps are not recommended as radiation sources for plant growing [**34**].

Xenon lamps are able to most nearly duplicate the solar spectrum and irradiance. However, xenon lamps are expensive and generate ozone, which is toxic to plants and humans. The spectrum of the emitted photons has large quantities of infrared radiation. Infrared radiation cannot be used by plants and increases the cooling requirements for the growth area. Consequently, xenon lamps have only limited use in experimental growth chambers and are not recommended for the use in high productive greenhouses [**34**].

Sulfur Lamps, also known as microwave-powered lamps, are electrodeless lighting devices. Generally, a sulfur lamp consists of a quartz bulb filled with sulfur vapor and small amounts of argon vapor. The vapor is excited by microwaves generated by a magnetron. The excitation of the atoms results in an emission of photons [**35**]. The spectrum of sulfur lamps is comparable to the suns. However, the intensity of the infrared band is lower for sulfur lamps. The spectrum of a sulfur lamp compared to PAR is shown in Figure 3-17. Consequently, the heat production of microwave-powered sulfur lamps is low. The advantages of sulfur lamps are their small size and their nearly sun-like spectrum. The efficiency for the conversion of electrical energy to radiation is higher than for HPS lamps, but due to the low efficiency of the magnetron the overall efficiency is lower than that of HPS lamps. The average lifetime of sulfur lamps is around 20000 and the degradation of the radiation output is relatively low, leading to 90 % of the original value [**34**].

Light-emitting diodes (LED) are semiconductor devices which convert electricity to radiation. There are three types of LEDs suitable as radiation sources for plants: discrete LEDs, printed-circuit LEDs, and phosphor-based LEDs. LEDs are a comparatively new technology. The efficiency, lifetime and output are still increasing, while the costs are decreasing through the raising demands. The small size, high efficiency and long lifetime compared to other lighting sources make them very interesting for the usage in plant growing systems. Unlike other lamp types, the light output of LEDs is current controlled. Hence, the brightness directly affects the required power consumption [**34**].

Discrete LEDs emit photons with wavelengths in a narrow spectrum, depending on the construction material. Usually, the spectral band is only 50 to 100 nanometers wide. Consequently, LEDs with different colors are required to provide the light spectrum that plants need. In past studies red, yellow-green and blue LEDs were used in combination. For the spectrum from blue to green (460 - 550 nm) indium gallium nitride (InGaN) and for the spectrum from yellow to red (560 – 630 nm) aluminum gallium indium phosphide (AlGaInP) is used as the base material. Figure 3-18 shows the spectrum of a blue, a yellow and a red discrete LED compared to PAR. According to reference [**36**], commercially available LEDs with more than 20 % efficiency are available and efficiencies over 50 % are expected in the next decade.

The *printed-circuit LEDs* are small and applied on wafers in large numbers. This type of LED has no plastic lenses like discrete LEDs. The package density of printed-circuit LEDs is high, reaching up to 132 LEDs in an area of 6.25 cm^2. This technique provides bright light levels. Furthermore, each LED can be fabricated out of different materials, and therefore, different colors are feasible. Consequently, the color mixture of printed-circuit LED arrays can be adapted to the spectral needs of plants. However, it is not possible to replace a single broken LED. To repair a printed-circuit LED, the whole array has to be replaced by a new one [**37**].

Phosphor-based LEDs, also known as white LEDs, are the combination of the common LED technology with the technique of fluorescent lamps. Usually, a single blue LED made of gallium nitride (GaN) is used together with different mixtures of phosphor to generate a uniform, sun-like white light. Therefore, the inner side of the bulb of a bluish LED is coated with a phosphor mixture. The phosphor starts to emit a broad spectrum of light when hit by the photons generated by the LED. The broad spectrum from 500 to 700 nanometers could make this type of LEDs suitable for plant growing. However, this technology is currently under development to replace the commonly used incandescent lamps in household. Consequently, progress in the commercialization of the technique is expected in the near future [**36**].

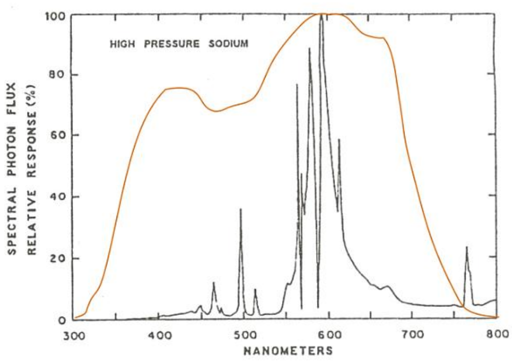


Figure 3-12: HPS lamp spectrum compared to PAR (orange line) [34]

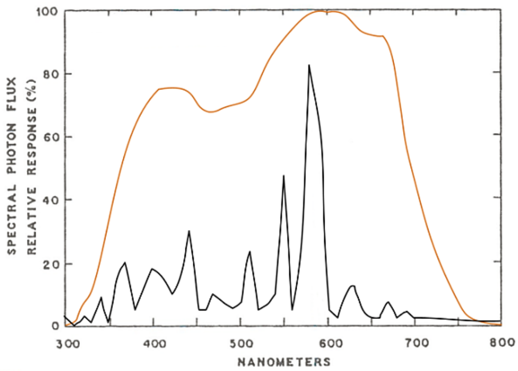


Figure 3-13: MH lamp spectrum compared to PAR (orange line), derived from [38]

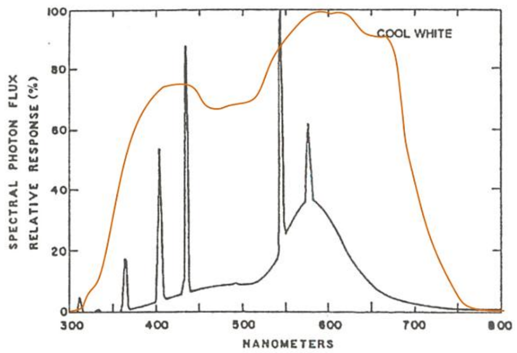


Figure 3-14: Fluorescent lamp spectrum compared to PAR (orange line) [34]

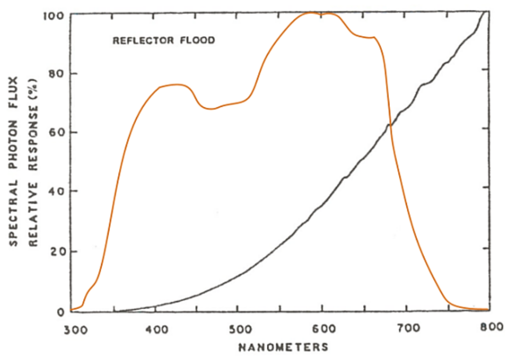


Figure 3-15: Incandescent lamp spectrum compared to PAR (orange line) [34]

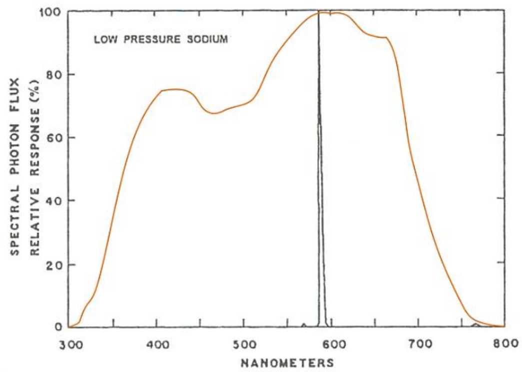


Figure 3-16: LPS lamp spectrum compared to PAR (orange line) [34]

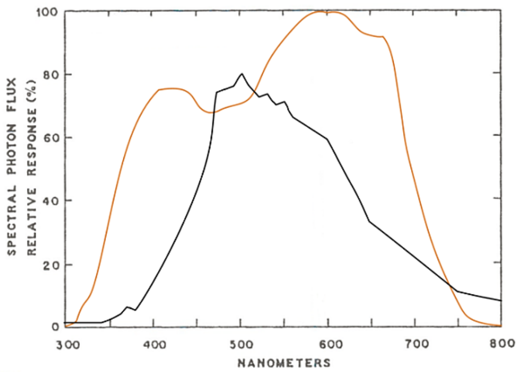


Figure 3-17: Sulfur lamp spectrum compared to PAR (orange line), derived from [38]

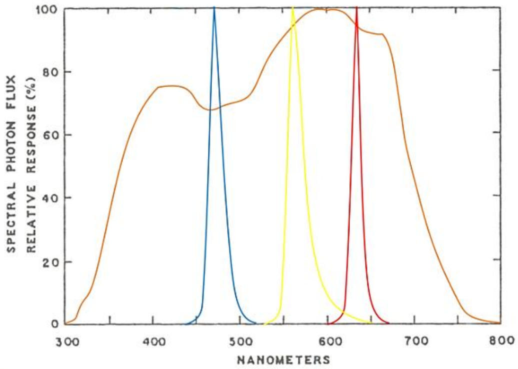


Figure 3-18: Spectrum of blue, yellow, red discrete LEDs compared to PAR (orange line) [34]

Natural Lighting

The utilization of sunlight is the basic form for providing plants radiation. All plants originated on Earth are adapted to use the energy provided by the Sun's radiation. Greenhouses with natural lighting systems are established all over the world to grow food in a controlled environment. Furthermore, natural lighting systems have the lowest power demands, compared to electrical and hybrid lighting. Hence, the use of sunlight for growing plants in space and on other planetary bodies looks promising. There are two ways of using the sun as radiation source: direct natural lighting and indirect natural lighting.

In *direct natural lighting* systems the sunlight passes windows or transparent walls to reach the growth area. Comparable to electrical lighting systems, direct natural lighting systems need a powerful heat rejection system to reduce the heat generated by the infrared radiation of the Sun. The environmental conditions of the nearest planetary bodies, Moon and the Mars, complicate the use of direct natural lighting systems. One day on Moon is usually 28 Earth days long, hence there is 14 days sunlight followed by 14 days night. However, some locations at the poles of Moon with nearly continuous sunlight exist. The day length on Mars is similar to Earth, but the higher distance from the Sun lowers the average sunlight intensity to 43 % of the terrestrial and due to the higher excentricity of the Martian orbit, the variation of intensity is higher than on Earth. The inclination of Mars causes long seasonal periods, which leads to long winter periods without sunlight at the poles. Other problems for the usage of direct natural lighting on Mars are dust and dust storms. The wind on Mars is able to carry dust over long distances and periodical strong and long lasting dust storms appear. The dust covers the outside surfaces of windows and have to be removed to provide enough sunlight for the plants. However, during dust storms the amount of sunlight reaching the surface of Mars is too low for the demands of plants. Besides the problems with environmental conditions at the location, the direct usage of sunlight can be more effective, and less mass and cost intensive than electrical lighting [**39**].

Indirect natural lighting systems also utilize the energy of solar radiation to provide energy for plant growth. They use reflectors, concentrators and plastic optic fibers to collect and distribute the sunlight over the whole growth area. Reflectors are polished surfaces or mirrors and can be up to 95 % effective as direct sunlight systems, but contrary to those systems reflectors reduce the heat input into the growth area and the heat can be directly rejected to the environment without the need of additional radiators [**39**]. Concentrators usually consist of a parabolic mirror and a collector. The mirror concentrates the incoming sunlight at the collector and the collector feeds fiber optic cables. These cables deliver the sunlight to the internal lighting system inside the greenhouse and provide radiation for all plants. The power demand for tracking the Sun is relatively low. The disadvantage of fiber optic cables is their low efficiency. The longer the cables are, the lower is the efficiency. However, currently new technologies for fiber optic cables are under development and new optic cables with higher efficiencies are expected in the near future. Besides the low heat input and low power demand of indirect natural lighting systems are other advantages. Fiber optic cables can be easily replaced and therefore, it is possible to adjust the location of the light sources inside the greenhouse. Furthermore, the cables can be used for intracanopy lighting which has advantages over other lighting distribution systems, see Chapter 3.4.3.3 [**31**].

Hybrid Lighting

Hybrid lighting systems combine electrical and natural lighting. Both of these have their disadvantages, especially the high power demands of electrical lighting, which can be up to 45 % of the total power demand of a greenhouse [**35**], and the dependency on the sun of natural lighting systems. Hybrid lighting systems can combine the benefits of both electrical and natural lighting to compensate their weaknesses. During sunshine the energy of the solar radiation can be utilized for the plant growth, and to generate and store electrical energy. In night periods the stored electrical energy is converted back to radiation for the plants by using an electrical lighting system.

3.4.3.3 Lighting Strategy

The previous chapter described the different types of light sources and their advantages and disadvantages. However, not only the lighting type, but also the lighting strategy affects the plant growth and the efficiency of the lighting control subsystem. There are three options for lamp positioning inside greenhouses:

- overhead lighting,
- sidewise lighting or
- intracanopy lighting.

Overhead lighting is the common strategy of positioning lamps. Thereby, the light sources are attached to the ceiling of the greenhouse. The intensity of light decreases exponentially when increasing the distance to the source. Therefore, the radiation source has to be close to the leaves of plants to provide enough intensity while reducing the power demand. Due to the plant growing, the distance between lamps and plants has to be adjusted to different plant development stages to ensure a sufficient lighting and reducing the thermal loads to the leaves. A problem of overhead lighting is shading of lower leaves by those above them, which leads to net carbon loss via respiration and underdevelopment of plant parts. To reduce the effects of shading, the walls of greenhouse modules can be painted white or covered with polished surfaces to reflect the radiation and provide some light from the sides. When reflectors are used, it has to be assured, that no spectral shift of the reflected light occurs, because this can cause several problems concerning thermal and plant issues. But even with reflective surfaces at the walls, shading cannot be totally avoided with overhead lighting [**34**].

Sidewise describes a lighting strategy, where lamps are attached to the walls of the greenhouse module. This lighting strategy requires a larger amount of space compared to overhead lighting, but the power demand can be reduced by this type of lighting strategy. However, sidewise lighting also creates shading of plants that are further away from the walls and therefore, the light distribution is suboptimal [**37**].

Intracanopy is the provision of lighting from the inside of the plant canopy. Thereby, the lamps are located close to the leaves or even touching them. Consequently, this lighting strategy is only applicable with low temperature light sources, which do not harm the plants. Promising systems for intracanopy lighting are plastic optic fiber cables, LEDs, or light tubes. Due to the close distance between leaves and lamps, the power demand of intracanopy is lower compared to overhead and sidewise lighting. However, a lighting system with intracanopy lighting as a sole source of radiation would be complex. A combination of overhead and intracanopy lighting can increase the edible biomass, decrease the power demand and solve problems with shading of leaves [**37**].

3.4.3.4 Atmospheric Composition

The atmospheric composition inside greenhouse modules affects the plant growth and the humans' ability to work. For plants the percentage of carbon dioxide in the air is an essential factor for their welfare and growth. For humans a suitable amount of oxygen is required to survive, as described in Chapter 2.2. Furthermore, the amount of carbon dioxide in the air is also important for the health of the crew, who work in the greenhouse. There are three possible options of an atmospheric composition in greenhouses for space applications:

- local planetary atmosphere,
- an earth-like atmospheric composition or
- an atmosphere enriched with carbon dioxide.

The usage of a *local planetary atmosphere* in a greenhouse is a theoretical option. In our solar system is no other known planetary body with an atmosphere suitable for plant growth. However, some atmospheres contain elements that can be used in greenhouses. Especially the carbon dioxide of the Martian atmosphere, see Chapter 2.1.2, could be extracted and injected into the atmosphere of greenhouse modules to provide higher concentrations.

An *earth-like* atmosphere is the simplest way of an atmospheric composition inside greenhouses and provides enough carbon dioxide to sustain plant growth and enough oxygen to allow humans to work without the need of respiratory protection devices. Every carbon dioxide concentration below the terrestrial concentration of 300 to 350 ppm decreases photosynthesis and consequently, plant growth [**40**]. The advantage of an earth-like atmosphere is that the atmosphere control system of the habitat can be used to maintain the atmosphere inside the greenhouse. Furthermore, no airlocks are required to seal the atmosphere of the greenhouse from that of the habitat.

Any atmospheric composition with a carbon dioxide level above the terrestrial is named an atmosphere *enriched with* CO_2. The responses of plants to elevated concentrations of carbon dioxide depend on the plant species, developmental stage, irradiance, temperature, mineral nutrition, and the size of the root zone. Table 3-12 shows a summary of the influences of a CO_2 enriched atmospheric composition on different processes of crop plants. The regulation of the CO_2 is quite difficult, because both plants and humans affect the CO_2 in different ways. The exhaled air of a working human contains 4 to 5 % carbon dioxide. Therefore, the amount of CO_2 in a sealed environment rises within in a few minutes to more than the tenfold of the normal level. Plants consume CO_2 to metabolize it in the photosynthetic process. Photosynthesis requires energy in form of radiation. Consequently, the level of CO_2 falls during lighting periods. Without the energy of light, photosynthesis stop and the CO_2 rises again due to respiration of plants up to twice as normal [**40**].

Table 3-12: Responses of crop plants to an increase in CO_2 concentration above earth-like atmosphere [40]

Process	Effects on Plants
Leaf photosynthetic rates	Increase in all plants on first exposure. Little response above 1000 ppm and levels above 2000 ppm may be toxic.
Inhibition of photosynthesis by source-sink imbalance	Response occurs in many species.
Leaf transpiration rate	Decrease in all plants.
Leaf anatomical and biochemical adaption	Leaf area, weight per unit area, thickness and number of mesophyll cell layers increase in many species.
Canopy leaf area	Usually increases.
Carbon partitioning among organs	Proportion of carbon going to roots and stems is increased in many, but not all, species.
Branching, flowering and fruiting	Initiation and/or retention of these organs are increased in many species.
Fruit and seed	Increases in number and/or size of fruits and seeds.
Canopy water-use efficiency	Increase in photosynthesis or yield contributes more than reduction in transpiration.
Yield	Increases 32 % on average between 300 and 660 ppm for plants in favorable conditions.

3.4.3.5 Trace Gas Treatment

Trace gases or air contaminants are an underestimated source of problems in closed environment systems. Until today only little research is done in this field, because of the wide spectrum of potential sources. The usual small air volume of closed environments emphasizes the effects of trace gases, which are generally never or rarely seen in the terrestrial ecosystem. Air contaminants are sporadically produced by painting, cleaning or remodeling structures and systems inside greenhouses. In addition to the sporadic production, the outgassing of some materials, mainly plastics, causes a constant source of toxic elements. Furthermore, the ethylene exhaled by plants has to be treated. Table 3-13 shows a summary of sources and effects of some toxic compounds identified during studies. Most of the addressed problems can be solved by choosing different, non-toxic materials or changing the design of systems. There are three options of handling trace gases:

- neither monitoring nor treatment,
- monitoring of the amount of air contaminants or
- the combination of monitoring and separation of trace gases.

A greenhouse with *neither monitoring nor separation* of trace gases is no suitable option for a controlled environment. The damage and symptoms caused at plants would be not repairable and could lead to diseases of the humans who ate the plants.

Monitoring of trace gases is the least option that has to be done in a closed environment. To monitor the contaminants several portable and stationary measurement systems exist.

A combination of *Monitoring and Separation* of traces gases is essential for every long term mission in closed environments. On Earth the exchange of the air of a greenhouse several times per day and the leakage of earthbound systems is sufficient to pretend the plants of harmful concentrations of contaminants. However, ventilation is no option in spacecraft and the leakage of a closed environment in space should be as low as possible. Consequently, mechanical and chemical filters are required to separate the trace gases out of the air. Activated charcoal filter systems are able to absorb most, but not all, of the contaminants. Some trace gases need more complex filter mechanism. The best way to deal with trace gases is the avoidance of materials that are potential sources [**41**].

Table 3-13: List of sources and symptoms of some harmful compounds [41**]**

Compound	Source	Caused Symptoms
Cyclohexylamines	Caulking compounds, steam	Leaf bleaching, leaf chlorosis, stunting of plants, downward curling of leaves, abscission of leaves
Diputyl phthalate	Flexible polyvinyl chloride tubing, glazing strips, hoses, pots, latex paint, aluminized plastic sheeting	Leaf bleaching, leaf chlorosis, stunting of plants, cotyledon necrosis
Mercury	Thermometers	Stunting of plants
Xylene	Paint	Stunting of plants
Ethylene	Ballasts, plants	Abscission of leaves
Ethylene glycol	Liquid in cooling systems	Leaf chlorosis, stunting of plants, downward curling of leaves

3.4.3.6 Temperature Control

The temperature of matter represents its thermal energy content. As in every metabolic organism the temperature influences the physiological and metabolic processes of plants. Consequently, the temperature inside a greenhouse has to be monitored and regulated to suitable conditions for plants. Plants are sensitive to temperature below and above their comfort zone. Lower temperature can suppress growth and fruit development, while high temperatures can cause damage to leaves, roots and other plant parts. Furthermore, high temperatures benefit transpiration of plants, which can lead to an imbalance in their water status. Plants interact with the thermal environment through conduction, convection and radiation. The heat transfer by conduction is relatively small compared to the other two. Conduction only occurs, when the plant is in contact with solid or liquid media. The effect of forced convection on plants in greenhouses is generally larger than that of natural convection, because of the air movement caused by ventilation system. The impact of radiation on the thermal environment inside greenhouse modules is significant. The surfaces of plants absorb a broad spectrum of radiation, but only a small amount is used for photosynthesis. The remaining radiation is reflected and shifted to longer wavelengths in the infrared spectrum. Consequently, the reflected radiation heats the environment around the plants.

Temperature control is necessary for greenhouse modules to provide a suitable environment for plant cultivation. The lighting system is the main source for thermal energy. Lamps heat the air by converting electrical energy to thermal energy and by emitting of infrared radiation. Furthermore, the re-radiated red shifted emissions of plants cause a rise in temperature.

Consequently, the primary task of the thermal control subsystem during lighting periods is cooling the inside of the greenhouse. Heat exchangers using chilled water or ethylene glycol are the commonly used cooling system. During dark periods, heating units could be required to maintain a warm enough air temperature. Therefore, electrical resistance heaters are used. The temperature control system can be designed in three different ways:

- controlling the temperature of the whole greenhouse,
- temperature control for each plant species or
- temperature control per growth unit.

Control limited to the *whole greenhouse* is the simplest way to maintain the temperature. All plants will be exposed to the same temperature. Therefore, the average temperature inside the greenhouse would be a compromise between the requirements of all cultivated plants. In this case the plants' yield would be not the potential maximum.

A temperature control adapted to *each plant species* can maximize the biomass production and yield. The complexity of such systems is higher than for control systems for the whole greenhouse. More sensors, larger ventilation and cooling systems are required. Furthermore, barriers between different plant species are necessary to maintain the temperature difference. Consequently, the masses of the thermal and air control subsystems are higher for the temperature control of each plant species.

The monitoring and controlling of the temperature of *each growth unit* is challenging and requires a complex system of sensors, pipes and fans. However, separate thermal controls for each growth units can increase the yield due to specific temperatures. The increase in food output has to be traded against the rise of complexity and mass of the system.

3.4.3.7 Photosynthetic Period

The *photosynthetic period* is another factor related to the lighting control subsystem. Besides the provision of radiation with suitable wavelengths, see Chapter 3.4.3.2, the quantity of radiation and the duration of the exposure to light affect the plant health and growth. The quantity of radiation is named photosynthetic photon flux (PPF). The PPF is the amount of photons of a specific wavelength that flow through an area in a defined timespan. The unit of PPF is micro moles per square meter per second for a specific waveband, $\mu mol/(m^2*s)$. The analysis of the waveband is important to compare the PPF of different greenhouse concepts. Furthermore, it has to be investigated how long the PPF is applied to the plants.

The product of PPF and time is the quantity of energy delivered to the plants. As long as the quantity of energy is constant, the growth rates of plants are similar. Consequently, continuous exposure to light is possible to reduce the PPF and therefore, the energy required for electrical lighting. When a continuous photosynthetic period is applied it has to considered, that the temperature of the leaves can rise to a critical level. Usually, a day-night cycle of 16 hours light exposure and 8 hours darkness with a PPF of 400 to 500 $\mu mol/(m^2*s)$ for the waveband of PAR leads to suitable growth rates. However, the PPF and duration of the photosynthetic period are plant specific and should be adjusted to every plant species to maximize the yield [**34**].

3.4.3.8 Humidity

Humidity, also known as atmospheric water vapor, has several effects on the behavior of plants. The energy balance of plants is indirectly affected by humidity. The direct effect of humidity is the influence on the gas exchange between plants and their environment. Hereby, the most significant impact of atmospheric water vapor is on transpiration: when humidity decreases, transpiration increases. The plant water status is the balance of water gained by roots and water evaporated over the surface of leaves. Low transpiration, as well as high, can lead to an imbalance of the water status and therefore, can damage the plants or cause sicknesses. High humidity stimulates the stomata of plants, small openings on the leaf which can sense humidity and regulate the transpiration rate, to remain closed. Hence, the transpiration and gas exchange is stopped, which leads to a reduced carbon dioxide intake reduced photosynthesis and therefore, lower yields. Plants use transpiration to cool their body in a same way humans do. Consequently, transpiration causes a heat transfer from plants to their environment.

Humidity also affects the temperature control subsystem by increasing specific heat of the air and due to the heat energy transfer caused by evaporation and condensation. The effects of humidity on the chemical and biological environment of greenhouse modules are less significant. A continuous measurement and control of humidity is challenging, but necessary. The humidity control mechanisms are usually a combined task of air, water and temperature control subsystems. The usually small volume of closed environments leads to more extreme levels of humidity, because the gas exchange with the outside is negligible. The control of humidity has high energy demands due to the nature of energy required for evaporating and condensation of water vapor. Condensation is used to reduce the humidity inside the greenhouse. Therefore, surfaces with a temperature at or lower the dew point are required. The condensed water has to be collected and removed out of the greenhouse. To higher the humidity, water vapor is injected to the air.

Several definitions and units are known. For the analysis during this thesis the terms absolute humidity and relative humidity are used. The absolute humidity is also known as water vapor density or water vapor concentration and is the total amount of water inside a specific volume of air. The unit is gram per cubic centimeter, g/cm^3. The ratio of water vapor contained in the air to that at saturation point at the same temperature is defined as relative humidity and expressed as percentage. The usage of relative humidity for evaluation process is problematic due to the dependency on the air temperature. However, relative humidity is a commonly used value and as long as the temperature is also investigated, relative humidity can be established as factor [**42**].

3.4.3.9 Air Temperature

The a*ir temperature* influences plants as described in Chapter 3.4.3.6. Therefore, an analysis of the air temperature inside greenhouses of different concepts is essential. The temperature has to be reported as average and range in degree Celsius, °C. Furthermore, the location of the temperature is worth knowing, because temperature gradients between sections of the greenhouse may exist.

3.4.3.10 Atmospheric Pressure

The *atmospheric pressure* inside greenhouse modules affects the structural design, the leak rate and the behavior of humans. According to references [**43**] and [**44**], the effects of the atmospheric pressure on plants are negligible. However, the transpiration rate is slightly increased in environments with an atmospheric pressure lower than the terrestrial average.

The design of pressurized modules for space applications is challenging, because the structure of spacecraft have to withstand the pressure difference between the inside of the module and the ambient pressure at the location. Furthermore, the higher the pressure difference between the inner and the outer of the module is, the higher the leakage rate. Low pressure modules can be designed to reduce the structural loads and therefore, the mass of the module [**44**]. In addition a reduced atmospheric pressure lowers the leakage rate. Consequently, a low pressure environment inside greenhouse modules is applicable, as long as the human requirements described in Chapter 2.2 and the demands of plants are met [**45**]. The atmospheric pressure has to be reported in kilopascal, kPa.

3.4.3.11 Carbon Dioxide and Oxygen Partial Pressure

The *CO_2 partial pressure* directly affects the yield and growth rates of plants, as described in Chapter 3.4.3.4. Therefore, it is important to analyze the carbon dioxide level of the atmosphere inside greenhouse modules. The photosynthetic periods of plants lead to an oscillation of the concentration. Consequently, the range and the average of the concentration have to be investigated. Several units for gas concentrations exist, the most commonly used units are the partial pressure and parts per million of volume. The proposed unit of this thesis is the partial pressure in kilopascal, kPa [**45**].

The *O_2 partial pressure* mainly influences the work ability of humans inside greenhouse modules. The effects of different oxygen levels on humans are described in detail in Chapter 2.2. While humans need a sufficient partial pressure of oxygen, plants are able to grow without O_2. Furthermore, the efficiency of photosynthesis increases under lower concentrations of oxygen [**44**]. Consequently, a compromise between the efficiency of plants and the work ability of humans inside the greenhouse has to be considered. Options for reduced oxygen levels are oxygen masks or hermetically closed suits for the crew working inside the greenhouse, or fully automated greenhouses, which do not need human presence to growth and harvest plants. Oxygen partial pressure is commonly reported in kilopascal, kPa [**45**].

3.4.4 Agricultural Factors

3.4.4.1 Definition

Agricultural factors refer to the tasks and requirements of the agricultural subsystem defined in Chapter 2.5. Consequently, the established agricultural factors are used to analyze and evaluate the plant cultivation subsystem, the nutrient delivery subsystem and the harvest & cleaning subsystem. Nine agricultural factors are investigated, five qualitative and four quantitative factors. The Plant Cultivation Subsystem (PCS) is analyzed and evaluated on the used growth medium, the installed plant monitoring system, the plant mixture, the planting sequence, the cultivated plants, the biomass productivity, the specific growth area and the grow height. The investigation of the nutrient supply is used for the analysis and evaluation of the Nutrient Delivery Subsystem (NDS). For the Harvest & Cleaning Subsystem (HCS) no factors are defined, because the provided tools and stuff of this subsystem are independent from the design of the greenhouse module. However, the size of the HCS is proportional to the size of the greenhouse module. Table 3-14 shows a list of all agricultural factors split into quantitative and qualitative factors.

Table 3-14: List of Agricultural Factors

Qualitative Factors	Quantitative Agricultural Factors
Growth Medium	Cultivated Plants
Plant Monitoring	Biomass Productivity
Nutrient Supply	Specific Growth Area
Plant Mixture	Growth Height
Planting Sequence	

3.4.4.2 Growth Medium

The growth media of greenhouse modules are the substances in which the roots of the cultivated plants reach and absorb the nutrients. The selection of an appropriate growth media for greenhouse modules is challenging, because of several requirements an optimal growth medium has to fulfill. Basically, the available growth media can be divided into the three categories:

- soil,
- soil-like or
- soilless.

Soil as growth medium can be either terrestrial or extraterrestrial soil. Soil-like growth media are usually substrates, thereby, inert and organic substrates are considered. Soilless agriculture methods are hydroponic and aeroponic. They do not use any kind of soil or substrates.

Soil

The growing of plants in *terrestrial soil* is the most commonly used cultivation method on Earth. Soil agriculture is utilized by humans since several thousand years. Consequently, the use of soil as grow medium in open fields and greenhouses is well understood. However, terrestrial soil as growth medium for environmentally closed greenhouse modules in space is not suitable. The launch and transportation costs for terrestrial soil are high compared to other growth media. According to reference [**45**], problems with microbiological contamination are unpredictable and can cause a complete failure of the greenhouse module. Furthermore, the handling of plants grown in soil during planting and harvesting under microgravity is difficult. Microgravity also inhibits drainage leading to water-logged soil, which can cause anaerobic reactions in the soil. Additionally, the absence of convection under microgravity prevents aeration of the roots. Another problem with soil as growth medium is the potential absorption of trace gases from the air, which could lead to problematic chemical reactions in the soil. Since plants do not need terrestrial soil to grow as long as all required nutrients are provided, terrestrial soil is not recommended for the use in space based greenhouse modules [**45**].

Extraterrestrial soil as growth medium shares the disadvantages of terrestrial soil, except the transportation costs for the soil are absent. However, for the conversion of extraterrestrial surface material to an appropriate growth medium requires special devise and systems.

NASA undertakes research in the usage of lunar surface material, also known as regolith. However, in its pure form, regolith is not suitable for growing plants, because it inhibits aeration and water flow to the roots. Furthermore, regolith contains only small amounts of the required nutrients for plants and the potentially of toxicity of chromium and nickel in regolith is not identified [**46**]. According to the references [**46**] and [**47**], growth media derived from local planetary surface material look promising for the usage in greenhouse modules, but further research is required to precisely determine their properties and growth conditions.

Soil-like

For *inert substrates* as growth medium commonly perlite, rockwool, polystyrenes and zeolites are available. According to reference [**46**], zeolites are the most promising inert substrate for greenhouse modules. Zeolites are crystalline, hydrated aluminosilicates containing loosey-bound ions of potassium, sodium, calcium and magnesium. In nature about 50 zeolites exist and several hundreds were developed by mankind in the last decades. The channels and pores zeolites generally have, allow the storage of nutrient cations without changing the zeolites themselves. Consequently, an inert substrate can act as a nutrient reservoir for plants. Furthermore, zeolites are sterile to pathogenic microorganisms, which usually cause problems in soil based greenhouse modules [**46**]. Zeoponic agriculture is still under development and further research is required to determine the benefits and disadvantages of this cultivation method. First experiments show the potential of zeoponics to overcome soil as growth medium. However, zeolites share some disadvantages with soils [**31**]. The major disadvantage is the degradation of the zeolites over time, which results in a demand of new zeolites after some growth periods. The new zeolites have to be delivered from Earth or produced in the habitat. Both options increase the resupply respectively launch mass of the greenhouse module.

Organic substrates like straw or hay can be used as potential growth medium for extraterrestrial greenhouses. However, organic substrates can react with the nutrient solution and will decay over time, which increases the growth of pathogenic microorganisms inside the substrate. Furthermore, the rotting of organic substrates creates trace gases and substances which have to be treated and the decayed substrate has to be replaced with new one frequently. Consequently, organic substrates are not recommended for the use in extraterrestrial greenhouse module, because of the unpredictable consequences of occurring bacteria, fungi and other microorganisms.

Soilless

Hydroponic agriculture is a soilless cultivation method, because the roots of plants are hang in an aerated, circulating liquid. The liquid mainly consists of water, enriched with nutrients and oxygen. Reference [**45**] states, that hydroponic systems provide a precise control of nutrient composition, concentration, availability and pH. Hydroponic systems assure an appropriate of root zone oxygen and allow precise control of the root zone environment. Furthermore, low watering of plants cannot occur in these systems and it is not necessary to clean the growth medium between crops, because there is no solid growth medium. The nutrient delivery to the plants can be precisely controlled and maintained due to the concentration of nutrients in the water flowing around the roots. Another advantage of hydroponic agriculture is the possibility to recycle the used liquid nutrient solution, because it consists mainly of water. Plants grown in hydroponic cultivation systems have a higher harvest index compared to plants grown in soil. The harvest index is the ratio of edible biomass to inedible biomass of harvested plants. The higher harvest index results from a lower root mass of hydroponically grown plants. Since nutrients and water are continually available in hydroponic systems, plants need only small roots, which have only 3 to 4 % of the total dry weight, while the roots of plants cultivated in soil generally have a dry weight of 30 to 40 %. However, the advantages of hydroponic agriculture bring significant disadvantages with them. Greenhouse modules with hydroponic systems have a high system mass compared to other solutions, even higher than soil based systems [**45**]. Furthermore, the large surfaces covered with water can result in evaporation of water and consequently, increased humidity [**42**]. The transpiration rate of plants grown in hydroponic systems is higher than in soil grown plants [**48**]. Nevertheless, hydroponic agriculture is a suitable cultivation method for greenhouse modules in planetary habitats.

In *aeroponic* agriculture, the plants' roots are not located in any form of substrate and are not flowed around by water. They are hanging loosely in the air. Due to the absence of growth medium, the system mass for an aeroponic greenhouse module is low compared to the other cultivation methods. The nutrient solution is applied to the roots in the form of a fog created by sprayers and injectors. Consequently, the required amount of nutrient solution is lower than for other cultivation methods, because the nutrients are directly supplied to the roots [**45**]. Aeroponic cultivation systems provide perfect aeration of the root zone which is important for an optimal root zone development and plant growth [**31**]. The nonexistence of a growth medium leads to a negligible nutrient buffer capacity. Therefore, the nutrient solution has to be applied on the roots in regular intervals to assure an optimal plant growth. Furthermore, the nutrient composition and pH has to be controlled and adjusted frequently. The root zone of an aeroponic cultivation system has to be confined to avoid the contact of nutrient solution with the normal atmosphere of the greenhouse module [**45**]. The confinement of the root zone is complicated, because the nutrient solution usually is moderately corrosive and will damage any unprotected electronic and structural components. Furthermore, the nutrient solution can contain pathogenic microorganisms and the contact between them and other plants and especially crew members have to be avoided at any cost. According to reference [**45**], aeroponic systems are not recommended for the use in extraterrestrial greenhouse modules until the clogging of the sprayers and injectors can be eliminated, because the cleaning of sprayers and the replacement of broken injectors is complicated and requires too much crew time and spare parts.

3.4.4.3 Plant Monitoring

Plant monitoring is essential to maintain the optimum growth conditions of plants and to detect diseases or abnormalities. Several plant monitoring systems and sensors exist to observe plants during their growth. Environmental sensor systems for temperature, humidity and atmosphere composition can be used for indirect measurements of the plants' welfare. Fluorescent imaging systems can be used to observe the photosynthesis of plants. Therefore, a single leaf of a plant is irradiated with a defined light spectrum. The spectrum of the reflected radiation is measured and interpreted to achieve information about the photosynthetic efficiency. The nutrient uptake of plants can be investigated by determining the concentration of nutrients in the nutrient solution. The dimensions of plant parts like leaves, stems and blooms are measured manually or with the aid of laser imaging. Image sequences of plants over a defined timespan can be analyzed by special designed software tools to determine the growth rate. Furthermore, destructive investigation methods are available. These methods destroy a leaf or another plant part and analyze the residuals. However, destructive methods are only suitable for research greenhouse modules. For food production greenhouses edible biomass is valuable and should not be destroyed as long as other investigation methods are feasible. The plant monitoring established during this thesis does not evaluate the applied sensor system of the analyzed concepts, but rather evaluates the level of plant monitoring. The levels of plant monitoring:

- no plant monitoring,
- monitoring per plant species,
- per growth unit or
- per plant

are described in the following paragraphs.

No plant monitoring is only a theoretical option. Greenhouse modules without any plant monitoring are not suitable for space application, because the yield cannot be maximized. The welfare of plants inside such greenhouse modules cannot be observed appropriately and consequently, diseases and abnormalities can occur and lead to a complete failure.

Plant monitoring *per plant species* is the least option which should be established in greenhouse modules. Thereby, the development and health of one plant per species is observed. The analysis of this plant's status then represents the average of all plants of this species. This monitoring concept is inaccurate compared to the following to monitoring concepts. However, plant monitoring per plant species is suitable for short duration missions and test greenhouses.

Plant monitoring *per growth unit* is the optimal solution for extraterrestrial greenhouse modules which are usually subdivided into several growth units. A growth unit can contain only one plant species or mixtures of species which have the same lighting and nutrient requirements. Monitoring systems for growth units measure all conditions inside the unit and observe the development of a selected plant to estimate the health status of all plants inside this unit. Usually, each growth unit has its own sensor system for environmental parameter. Investigations of plants' physiology and welfare are undertaken by a mobile or robotic system that is responsible for several growth units and examines each unit frequently. Plant monitoring per growth unit is highly recommended for food production greenhouse modules, because this concept provides all required data for the maintenance of the module and maximization of the yield.

Monitoring of *every plant* requires more equipment than the other options and therefore, the complexity of the monitoring system is high. Furthermore, the monitoring of every plant is not necessary for the maintenance of greenhouse modules. In large greenhouse modules the monitoring of every plant is impracticable due to the potentially high amount of plants. However, the monitoring of every plant can be valuable in test greenhouses, were the responses of plants to different conditions is investigated.

3.4.4.4 Nutrient Supply

The nutrient supply is part of the Nutrient Delivery System (NDS) as described in Chapter 2.5. This factor describes the way nutrients are provided to the NDS. In extraterrestrial greenhouses the essential minerals for the plant growth has to be offered to the plants via the NDS. The NDS itself is responsible for an adequate mixture of different nutrients. Therefore, for each element of the mixture separate tanks exist. Usually, the nutrient mixture consists of different nitrates and sulfates in combination with water. The nutrients themselves can be provided as

- stored liquids and solids,
- by partial recycling or
- by full recycling of inedible biomass.

In *stored nutrient* concepts, nutrients are filled in tanks and taken from Earth with the launch of the greenhouse module. The mission time of greenhouse modules is restricted to the amount of nutrients contained in the tanks. For the extension of growth period, nutrients have to be resupplied from Earth regularly. This type of nutrient supply is only suitable for small, research or prototype greenhouse modules, because of the higher demand in required resupply mass compared to the other types.

Partial recycling concepts extract nutrients out of inedible biomass of harvested plants and therefore, are able to produce some of the required nutrients. Nevertheless, partial recycling systems cannot provide all required elements, because some of them are transferred to the metabolism of the crew while eating the edible biomass of plants. However, this type of nutrient provision reduces the resupply mass of nutrients and can provide up to 60 % of total inorganic nutrient weight and 20 % of total organic carbon required by plants [**45**]. Consequently, partial recycling concepts are suitable for mid-sized greenhouse modules.

Full recycling nutrient supply systems gain the nutrients due to the recycling of all inedible biomass produced by plants and all feces produced by crewmembers. This type of nutrient supply is a nearly closed loop system, but leakages and imbalances in bio-chemical processes prevent full closure. Nevertheless, a fully recycling concept requires only a very small amount of resupply mass for nutrients compared to the other two types. Two reduce the resupply mass to zero the extraction of nutrients out of extraterrestrial soil has to be investigated. Consequently, a full recycling concept is suitable for greenhouse modules in large and permanent extraterrestrial habitats and can reduce the dependency on resupply from Earth.

3.4.4.5 Plant Mixture

The plant mixture factor is established to analyze how plants of different species can be grown together in greenhouse modules. In greenhouses plants are grown as

- monoculture or
- polyculture.

In greenhouse modules with *monoculture*, only one plant species is cultivated per growth unit. This concept is the commonly used option for extraterrestrial greenhouse module concepts. Plant growth is predictable and every plant species receives their perfect nutrient solutions and optimal environmental conditions, because no compromise with other species has to be made. However, monoculture can lead to inefficient growth area use, when the plant allocation is not planned appropriately. The lower complexity compared to polyculture recommends monoculture for the use in greenhouse modules for space applications.

Polycultural greenhouse modules cultivate different plant species together on the same growth area. When the grown plants are selected carefully they can benefit from the presence of other plant species. However, polyculture is not suitable for every plant species and is only recommended when the selected plant combinations are extensively tested over several growth periods and generations and no incompatibilities are observed. Incompatibilities between plant species can induce underdevelopment or even the death of plants. Usually, most of the problems of polyculture occur in the root zone when the roots of one plant species dispense substances which are toxic to the root system of the other plant species. Furthermore, plants in a polyculture should have the same growth periods to assure seeding and harvesting at the same time, which is necessary to prevent damaging of plants during the processes. Consequently, polyculture can increase the biomass output per growth area, but should only be established when the welfare of all plants can be guaranteed.

3.4.4.6 Planting Sequence

The planting sequence describes the way plants are settled into greenhouse modules and directly affects the harvesting date of plants, assuming known growth durations. The sequence has to assure a continuous output of food and oxygen without or with only small fluctuations. Two planting sequences are discussed for the implementation in greenhouse modules [**49**]:

- staggered planting or
- batch planting.

Staggered planting sequences, also known as conveyor planting, provide a nearly continuous food and oxygen output, and carbon dioxide intake. This planting sequence is similar to the just-in-time-production known from several industrial branches. A predefined amount of plants of one species is seeded at the same time and consequently, harvested at the same time. Thereby, the number of seeded plants depends on the amount of food needed at the harvest date. Usually, staggered planting sequences do not produce surplus in food. Consequently, the required storage capacity and therefore, the buffers of food for cases of emergency are relatively small. Furthermore, the continuous production cycle causes a constant need in crewtime for maintenance [**49**].

In greenhouse modules with *batch planting sequences* plants are seeded in clusters at the same time. Hence, this type of planting sequence can neither provide a continuous food output or gas exchange rate. However, for some plant species, especially all sorts of cereals, batch planting is advantageous over staggered planting, due to crewtime savings in the processing of large quantities of grains compared to low quantities [**49**].

3.4.4.7 Cultivated Plants

In greenhouse modules cultivated plants are generally food plants. The botanic and biology have several classification for plants. However, for the analysis of greenhouse modules a classification system based on the major nutrient contained in plant species is established. According to the human requirements on different nutrients described in Chapter 2.2, this thesis proposes the division of food plants into:

- carbohydrate-supplying,
- protein-supplying,
- fat- and oil-supplying,
- vitamins- and minerals-supplying,
- and miscellaneous plants.

The classification system is based on reference [**50**]. Nevertheless, it has to be considered that plants naturally contain more than one nutrient. Consequently, some food plants can be classified in multiple categories. The following description of plant categories and plants is done very briefly. Due to the complexity of the crop selection for greenhouse modules, this topic has to be investigated in detail separately. For the analysis this thesis proposes the documentation of the cultivated plants and the allocated growth area per greenhouse module concept.

Carbohydrate-supplying plants contain high amounts of starch, sugar and other carbohydrates. Carbohydrates are generated by the plants during the photosynthesis and afterwards delivered to the growing parts and to the storage organs. They provide a high amount of energy when consumed and therefore plants that produce them are essential to feed a crew. Especially the carbohydrate-supplying plants with a high content of starch are important for the provision of energy to the crew. Thereby, cereals and potatoes are the commonly proposed plants [**50**]. Table 3-15 shows the amount of ingredients in different carbohydrate-supplying plants. The NASA recommends the cultivation of rice, wheat, white potato and sweet potato (batate) for their greenhouse module concepts [**23**].

Table 3-15: Ingredients of some carbohydrate-supplying plants per 100 g edible biomass [50**]**

	Wheat	Rye	Rice	Corn	White Potato	Sweet Potato
Water [g]	13.2	13.7	13.1	12.5	77.8	69.2
Protein [g]	11.7	8.8	7.2	8.5	2.0	1.6
Fat [g]	2.0	1.7	2.2	3.8	0.1	0.6
Carbohydrate [g]	60.9	60.7	74.0	64.0	14.8	24.0
thereof Starch [g]	58.1	52.4	72.7	61.4	14.1	19.5
Dietary Fiber [g]	10.3	13.1	2.2	9.2	2.0	3.1

Proteins are composed of amino acids. Plants are able to synthesize all required amino acids, while humans are incapable. Consequently, humans have to gather amino acids through their food. *Protein-supplying plants* contain high amounts of proteins, which are broke down to amino acids during the digestion. Afterwards the human body utilizes the gained amino acids to create the proteins required for the metabolism. The seeds of legumes have the highest content of proteins of all plants. Legumes are all sorts of beans, peas and lentils [**50**]. Table 3-16 shows the amount of water, protein, fat, carbohydrates and dietary fiber of some protein-supplying plants. Especially, soybeans are essential for the nourishment of humans with an extraterrestrial greenhouse module, because of their very high protein content compared to other protein-supplying plants combined with a high content of fat [**23**].

Table 3-16: Ingredients of some protein-supplying plants per 100 g edible biomass [50**]**

	Chick Pea	Garden Pea	Lentil	Soybean	Green Bean
Water [g]	11.0	11.0	11.8	8.5	11.6
Protein [g]	19.8	22.9	23.5	33.7	21.3
Fat [g]	3.4	1.4	1.4	18.1	1.6
Carbohydrate [g]	41.2	41.2	52.0	6.3	40.1
Dietary Fiber [g]	21.4	16.6	10.6	22.0	17.0

Fats and oils are the ingredients of plants with the highest energy density. Hence, *fat- and oil-supplying plants* are indispensable for the nourishment of humans with a greenhouse module. The fat and oil content of plants is naturally low. However, some plants develop seeds with high contents of fats and oils. These include soybean, rape, sunflower, peanut, several sorts of palms and olive trees [**50**]. Palms and sunflowers are not recommended for the cultivation due to their high growth height. As described in the paragraph about the protein-supplying plants, soybeans are strongly recommended for the cultivation in a greenhouse module. The cultivation of peanut and rape is also suitable [**23**].

Vitamins- and minerals supplying plants can be divided into vegetable- and salad-supplying, and fruit-supplying plants. Cooked plant parts served as side dish to energy providing food are commonly known as vegetables. While plant parts served uncooked are named salads. The relevance of vegetables and salads for the nutrition is their high content of vitamins, minerals and secondary ingredients which increase the taste of the food and benefits the health of the crew [**50**]. The vegetable- and salad-supplying plants shown in Table 3-17 are commonly recommended for the cultivation in greenhouse modules [**23**]. Fruit is commonly known as plant parts which have a sweet or sour taste and which are consumed uncooked. All fruit sorts are rich in vitamins and minerals. Consequently, they are of great importance for the daily nutrition [**50**]. Unfortunately, most fruits grow on trees or bushes, which make them less suitable for the cultivation in greenhouse modules. However, for some fruit, sorts with a low growth height and high food output exist, so called dwarf trees. These dwarf trees are a possibility to cultivate fruit in greenhouse modules. Strawberry plants are an exception. Their low growth height predestines them for the cultivation in greenhouse modules and can be served as incentive food to the crew [**31**].

Table 3-17: Ingredients of some vitamins- and minerals-supplying plants per 100 g edible biomass [50**]**

	Tomato	Cucu-mber	Pepper	Cab-bage	Lettuce	Spin-ach	Carrot	Radish	Straw-berry
Water [g]	94.20	96.80	91.00	90.50	95.00	91.60	88.20	93.50	89.5
Protein [g]	0.95	0.60	1.17	1.37	1.25	2.52	0.98	1.05	0.82
Fat [g]	0.21	0.20	0.33	0.20	0.22	0.30	0.20	0.15	0.40
Carbohydrate [g]	2.60	1.81	2.91	4.16	1.06	0.55	4.80	1.89	5.51
Dietary Fiber [g]	0.95	0.54	3.59	2.96	1.44	2.58	3.63	2.50	1.63
Minerals [g]	0.61	0.60	0.57	0.59	0.72	1.51	0.86	0.75	0.50
β-Carotene [mg]	0.15	0.40	2.50	0.07	1.44	4.70	7.80	0.01	0.02
Vitamin B1 [mg]	0.06	0.02	0.05	0.05	0.06	0.11	0.07	0.03	0.03
Vitamin B2 [mg]	0.04	0.03	0.04	0.04	0.08	0.23	0.05	0.03	0.05
Niacin [mg]	0.53	0.20	0.33	0.32	0.32	0.62	0.58	0.40	0.51
Vitamin C [mg]	24.50	8.00	180.00	45.20	13.00	52.00	7.00	27.00	64.0

Secondary food plants are plants which are not necessary for the nutrition of the crew, but can provide valuable substances or improve the psychological behavior. Herbs are an example for this category. They contain valuable essential oils and improve the taste of the usually monotonously tasting space food. Medicine producing, coffee or tea plants can also be cultivated in greenhouse modules. However, the production of food is the primary purpose of a greenhouse module. Nevertheless, the crew of permanent planetary habitats will have to cultivate secondary food plants as well.

Technically used plants produce substances or materials for other purposes than nutrition. These plants can provide fibers, wood, tanning agent, balsam, resin, wax, dyes or other valuable substances. The cultivation of technically used plants is only suitable in greenhouses of permanent habitats with a large crew to make the planetary outpost independent from resupply from Earth.

3.4.4.8 Biomass Productivity

The *biomass productivity* of greenhouse modules is a valuable factor for the evaluation of the efficiency. Thereby, biomass is the sum of inedible and edible dry mass produced by plants. The productivity greatly depends on the environmental conditions and on the cultivated plant species. This factor represents the efficient use of growth area, growth volume and electrical energy for the production of biomass due to the growing of plants. Consequently, the proposed units for these parameters are gram per square meter per day, g/(m^2*d) [**49**], gram per cubic meter per day, g/(m^3*d) [**49**], and gram per kilowatt hour per day, g/(kWh*d).

3.4.4.9 Specific Growth Area

The *growth area* is the area inside greenhouse modules used for plant cultivation. The size of the growth area directly affects the number of plants that can be grown and consequently, the food production. Furthermore, the growth area has to be large enough to provide enough edible biomass for the crew, but as small as possible to reduce the mass and size of the greenhouse module [**45**]. The overall growth area of greenhouse modules is measured in square meters, m^2. However, the ratio of area per crewmember is valuable to compare the efficiency of different concepts. The ratio is reported in square meters per crewmember, m^2/CM.

3.4.4.10 Growth Height

The *growth height* restricts the plant species which can be grown on the related growth area. For overhead lighting with high lamp temperatures it has to be taken into account that no plant part should touch the lamps. Consequently, the maximum growth height usually is smaller than the available distance between growth area and lamps. For the analysis of greenhouse modules the growth height and the related growth area has to be investigated. The proposed units are meter, m, respectively square meters, m^2.

3.4.5 Interface Factors

3.4.5.1 Definition

Interface Factors are used to analyze and evaluate the interactions between the greenhouse module and the habitat, respectively the crew. The three qualitative interface factors describe the utilization of the greenhouse module for water purification, air revitalization and the re-supply dependency of the habitat. The quantitative interface factors concern the food provision, the power and cooling demands of the greenhouse module, as well as the input and output of water, the required input of carbon dioxide and the oxygen output. Furthermore, the crew size the greenhouse can provide food for, the required work load to maintain the greenhouse module functions and the benefits to the psychological health care of the crew are quantitative interface factors. Table 3-18 shows a list of all mentioned interface factors split into qualitative and quantitative factors.

Table 3-18: List of Interface Factors

Qualitative Factors	Quantitative Factors
Water Purification	Food Provision
Air Revitalization	Power Demand
Resupply Dependency	Cooling Demand
	Water In-/Output
	Carbon Dioxide Input and Oxygen Output
	Crew Size and Crew Work Load
	Psychological Health Care

3.4.5.2 Water Purification

The main purpose of greenhouses in spacecraft or planetary bases is food production, but besides that, it can also be used for water purification. Plants absorb water through their roots and metabolize it during the photosynthesis. However, some of the water is evapo-transpired from the leaves to the air. Consequently, the humidity inside the greenhouses increases during the plants photosynthesis periods. The water vapor condenses on cold plates into liquid water. According to reference [**45**], the collected water should be potable water in many cases, but further purification with physico-chemical or biological filtration systems should be applied to assure that the water is free of any contaminants. Furthermore, reference [**45**] estimates the required cultivation area per person for full water purification from 3 to 5 m^2. Therefore, three possible options for the usage of greenhouse modules for water purification exist:

- none,
- partial or
- full

water purification.

The option *none* is used for greenhouses that are not used for water purification.

Greenhouses can also be used for *partial water purification*. In this case there are other systems inside the habitat which purify the water with physico-chemical or biological processes in addition to the greenhouse. Furthermore, some of the water can be taken from resupply or storage, while the greenhouse filters the residual amount of water.

The option *full water purification* means, that the whole potable and washing water for the crew is purified by plants grown inside the greenhouse and that there is no physico-chemical or other biological filtration systems for the water.

3.4.5.3 Air Revitalization

During the photosynthesis plants remove carbon dioxide from the air and exhale oxygen, while humans consume oxygen and exhale carbon dioxide. Consequently, a greenhouse can be used to revitalize the air for a crewed habitat. The metabolism of plants and therefore, the carbon dioxide intake and oxygen outtake depend on the plant species and several environmental factors, as described in Chapter 3.4.3.4. However, reference [**45**] estimates the required cultivation area from 6 to 10 m^2 per person for full oxygen recovery. There are three possible options for the usage of greenhouse modules for carbon dioxide removal and oxygen recovery:

- none,
- partial or
- full

air revitalization.

The option *none* is used for greenhouses that are not used for air revitalization.

Greenhouse modules can also be used for *partial air revitalization*. In this case there are other systems inside the habitat which clean the air with physico-chemical or biological processes in addition to the greenhouse. Furthermore, some of the air can be taken from resupply or storage, while the greenhouse revitalizes the residual amount of air.

The option *full air revitalization* means, that the greenhouse absorbs all of the carbon dioxide produced by the crew and provides enough oxygen to maintain the welfare of all humans inside the habitat. Furthermore, there are no physico-chemical systems for the air revitalization.

3.4.5.4 Resupply Dependency

The plant diversity of greenhouse modules describes the type of plants which are cultivated. The plant types are classified on their ingredients and are similar to the plant categorization in Chapter 3.4.4.7. Depending on the purpose of the greenhouse module the plant setting can be composed of plants:

- for fresh food,
- for energy food or
- for a quasi-full nutrition of the crew.

These three categories are the outcome of a trade study made for the Lunar FARM concept [**31**], further described in Chapter 4.1.3.

Greenhouse modules with a *fresh food* plant setup cultivate primarily vegetables with a high content of water. These vegetables lose quality and palatability after dehydration, stabilization and packaging. Consequently, the delivery of them to planetary outposts is not suitable. In a fresh food scenario crops like wheat or beans are not grown although they are very nutrient and efficient. They can easily supplied from Earth, because of their low lose in quality after dehydration and packaging. However, the high demand of resupply with energy food is the disadvantage of the fresh food scenario and is therefore, only suitable for short mission durations or small crews. The cultivation of fresh food is advantageous over nutrition solely from storage and can be used to cover 26 % of the daily energy intake of the crew. The benefits to the health of the crew are not negligible. Furthermore, the required growth area for the provision of fresh food is assumed to be 23 m^2 per crewmember and the required crewtime for the work inside the greenhouse module is relatively low compared to the other two scenarios. Consequently, this scenario should be the least option for a crewed mission to other planetary bodies [**31**].

The *energy food* cultivation scenario can be used for greenhouse modules to produce up to 67 % of the daily energy intake required by the crewmembers. To avoid an imbalance in the nutrition of the crew the other 33 % of the daily energy intake has to be provided by stored or supplied food from Earth. In an energy food greenhouse module only plant species with high energy density and small required growth area are selected for the cultivation. According to reference [**31**], eight crops which meet these requirements are beans, carrot, green onion, pepper, white potato, strawberry, tomato and wheat. The required growth area is estimated to be around 27 m^2 per crewmember. The work load for an energy food greenhouse is higher than for a fresh food one, but significantly lower than for a quasi-full nutrition scenario. The energy food option is suitable for medium duration missions [**31**].

Q*uasi-full nutrition* greenhouses can provide up to 98 % of the daily required energy intake of the crew. However, some essential vitamins, minerals and proteins have to be provided due to resupply from Earth. The purpose of this scenario is the achievement of nearly independency from Earth's resupply. The pure vegetarian diet and the limitation of some vitamins and minerals in plants make resupply from Earth indispensable. However, the resupply mass required is very low compared to the other two scenarios. The required growth area for a quasi-full nutrition is assumed to be around 77 m^2 per crewmember. Furthermore, the number of different plant species has to be considered to assure a diversified food composition. According to reference [**31**], the required crewtime for a quasi-full nutrition greenhouse module is high and can exceed the available work power of the crew. Therefore, a high level of automation is necessary for this scenario.

3.4.5.5 Food Provision

The *food provision* of greenhouse modules is the most important evaluation factors and represents the amount of edible biomass produced by the plants. The food output is affected by several environmental and agricultural parameters and additionally depends on the cultivated plant species. The proposed units for this factor are kilocalories per crewmember per day, kcal/(CM*d), and gram of dry mass per crewmember per day, g/(CM*d).

3.4.5.6 Power Demand

The intensive lighting required for growing plants causes high *power demands* for greenhouse modules. The required power is primarily dependent on the duration of the lighting periods and on the chosen lamp types. Usually, the required electrical power is not generated by the greenhouse modules, but rather generated in special facilities which provide the power for the whole habitat. Power demands are shown as total power consumption of the module in kilowatts, kW, and as power consumption per growth area in kilowatts per square meters, kW/m^2. The former value is required for the design of a suitable energy generation facility, while the latter value is beneficial for the evaluation of different greenhouse module concepts.

3.4.5.7 Cooling Demand

Whether electrical or natural lighting is used as radiation source for plants, the *cooling demand* is high during the lighting periods. When natural lighting is used, the cooling demand is affected by the incoming infrared radiation of the sun. In case of electrical lighting, the cooling demand depends on the power demand of the lamps. Nearly all of the electrical energy required for the lamps is converted to heat. Therefore, it can be assumed, that the cooling demand is equal to the power demand of the lamps used as radiation source. The proposed units for the comparison of different greenhouse concepts with respect to the cooling demand are kilowatts, kW, and kilowatts per square meters, kW/m^2.

3.4.5.8 Water In-/Output

The *water in- and output* streams of greenhouses depend on the amount of plants, the plant species and several environmental conditions. When transpiration water from plants is reused as potable or wash water for the crew, or for the watering of the plants, the inwards and outwards water streams should be nearly equal to each other. The proposed unit for analysis and evaluation of water in- and output of different greenhouse concepts is kilograms per square meter per day, $kg/(m^2*d)$. The average water streams of greenhouses are estimated from 5 to 10 $kg/(m^2*d)$ in reference [**45**].

3.4.5.9 Carbon Dioxide Input and Oxygen Output

The *carbon dioxide input and the oxygen output* of greenhouse modules depend on each other and on all parameters that influence the photosynthesis of plants. The unit for analyzing and evaluating the streams of CO_2 and O_2 is kilograms per square meter per day, $kg/(m^2*d)$. The estimated values for the carbon dioxide and oxygen streams are wide spread, due to the variety of factors that affect the metabolism of plants. However, reference [**45**] states the range of carbon dioxide input from 0.04 to 0.30 kg/(m^2*d) and the range of oxygen output from 0.03 to 0.22 kg/(m^2*d).

3.4.5.10 Crew Size and Crew Work Load

The factor *crew size* stands for the amount of humans that one greenhouse module can support with food, water and air. The supportable crew is directly proportional to the grow area and efficiency of the greenhouse. The crew size value is required for the normalization of other parameters and is reported as a number.

The *crew work load* is the time that the crew needs to fulfill a desired task. Usually, work time is restricted during space missions. The required time per task is a fix value. Consequently, the work load can only be lowered by reducing the number of tasks or due to the automation of processes. Since the number of tasks in greenhouses cannot be lowered without a decrease in yield, the work load has to be lowered through automation. Potential options for the automation of greenhouse modules are discussed in Chapter 3.4.2.7. Table 3-19 shows crew time values for different greenhouse and domestic activities achieved during the BIOS-3 experiments. Hence, the unit for the time requirement of greenhouse activities is man-hours per square meter per day, man-hours/(m^2*d).

Table 3-19: Crew time requirements for different activities (adapted from BIOS-3) [45**]**

Activity	Time Requirement
Greenhouse Activities	***[man-hours/(m^2*d)]***
Planting	0.0199
Harvesting	0.0199
Observation	0.0158
Preventative Maintenance	0.0475
Nutrient Solution Maintenance	0.0300
Wheat Grinding	0.135 man-hours/(d*100 g)
Domestic Activities	***[man-hours/(CM*d)]***
Food Preparation, Eating, Clean-up	1.70
Water Preparation	0.14
Personal Hygiene	0.39
Living Compartment Hygiene	0.27

3.4.5.11 Psychological Health Care

The crew's *psychological health care* is an important factor for the success of long-term space missions and permanent planetary outposts. The permanent isolation from Earth, the small volume, the potential of system and mission failures, and the risk to die are some of the broad spectrum of factors that influences the psychological health of the crew. The crew of spacecraft are tested and trained for the stresses of space missions, but nevertheless they are not immune to psychological sicknesses. Studies with small greenhouses onboard the MIR station and the ISS indicate that the crew's sentiment benefits from handling, growing and taking care of plants [**12**]. Besides the crew, plants are the only living creatures onboard a spacecraft. According to reference [**51**], Space Shuttle astronaut Mike Foale loved the experiments with greenhouses, because they reduced his irritability. Furthermore, reference [**12**] cites Salyut cosmonaut Valentin Lebedev, that plants were like pets for him during his missions.

Consequently, a greenhouse has to be designed to offer benefits for the psyche of the crew in addition to the provision of food, water and air. The interaction with the plants in a technically dominated environment passively offers benefits to the psyche of the crew [**43**]. Furthermore, special plants can be grown. Spices have a strong effect on the well-being of the crew, because they can make the commonly monotone food tastier. In addition, the provision of incentive food that is not required for the nutrition of the crew can improve the psyche of the crew [**51**]. When investigated greenhouse module concepts consider the psyche of the crew. The implemented options have to be investigated.

3.5 Summary

Chapter 3 starts with the description of the analysis and evaluation strategy proposed in this thesis in the first subchapter. For the developed methodology an analysis and one or more evaluation methods are required.

The second subchapter describes the selected analysis method, the Morphological Analysis (MA). The MA is suitable for the analysis of greenhouse modules, because it allows a systematic analysis of current and future options for the defined subsystems. Furthermore, the MA provides a multitude of combinations and permutations for the analysis goal and therefore, a framework for the following evaluation. The result of a MA is a Morphological Box which is hierarchically structured and provides an overview over all measurable factors related to the goal of the analysis.

The third subchapter introduces two suitable evaluation methods for greenhouse modules. The first one, the Equivalent System Mass (ESM), is developed for the evaluation of ECLSS and is advantageous for evaluation with respect to transportation costs. However, the ESM method cannot be used for the evaluation of qualitative and performance criteria. The second evaluation method, the Analytical Hierarchy Process (AHP), is a more general evaluation method. The AHP requires defined evaluation criteria, whereby qualitative and quantitative criteria can be established. The criteria are arranged in a hierarchy. For the reduction of bias, the weighting of the criteria can be executed with a group of experts. Consequently, the AHP is selected for the evaluation of greenhouse module concepts conducted in Chapter 4.

The fourth subchapter establishes analysis and evaluation factors for greenhouse modules and a detailed description for each factor is given. The factors are grouped to four major categories: fundamental factors, environmental factors, agricultural factors and interface factors. The factors can be divided in qualitative and quantitative factors. In total 46 measurable factors are identified during this thesis, 13 fundamental, 11 environmental, 10 agricultural and 12 interface factors. Table 3-20 shows a complete summary of all established factors and their possible options, respectively units. Thereby, the factors are arranged in a Morphological Box.

Table 3-20: Summary of all established factors, arranged to a Morphological Box

	Fundamental Factors		Environmental Factors		Agricultural Factors		Interface Factors	
	Name	**Options/Unit**	**Name**	**Options/Unit**	**Name**	**Options/Unit**	**Name**	**Options/Unit**
Qualitative Factors	Module Shape	Prismatic, Spherical, Hemispherical, Irregular	Lighting Type	Electrical, Hybrid, Natural	Growth Medium	Soil, Soil-like, Soilless	Water Purification	No, Partial, Full
	Arrangement of Growth Area	Shelves, Conveyor, Rotating Cylinder, Plain	Lighting Strategy	Overhead, Sidewise, Intracanopy	Nutrient Supply	Storage, Partial Recycling, Full Recycling	Air Revitalization	No, Partial, Full
	Distribution of Aisles	Center Aisle Two Shelves, Two Aisles Center Shelf, Two Aisles Three Shelves, Moveable Shelves	Atmospheric Composition	Local Planetary, Earth-like, Enriched with CO_2	Plant Monitoring	None, Per plant species, Per growth unit, Every plant	Resupply Dependency	Fresh Food, Energy Food, Quasi-Full Nutrition
	Module Structure	Rigid, Semideployable, Deployable, In-Situ	Trace Gas Treatment	None, Monitoring, Monitoring and Separation	Plant Mixture	Monoculture, Polyculture		
	Adaptability of Internal Configuration	Inflexible, Semi-flexible, Flexible	Temperature Control	Whole greenhouse, Per plant species, Per growth unit	Planting Sequence	Staggered, Combined, Batch		
	Level of Automation	None, Partial, Full						
Quantitative Factors	Specific Module Mass	[kg/m^2]	Photosynthetic Period	[µmol*h/(m^2*s)] for waveband [nm]	Biomass Productivity	[g/(m^2*d)], [g/(m^3*d)], [g/(kWh*d)]	Food Provision	[kcal/(CM*d)], [g/(CM*d)]
	Total Module Mass	[kg]	Humidity	[g/cm^3], [%]	Cultivated Plants	Species: [m^2]	Power Demand	[kW], [kW/m^2]
	Dimensions	[m]	Air Temperature	[°C]	Total Growth Area	[m^2]	Cooling Demand	[kW], [kW/m^2]
	Total Volume	[m^3]	Atmospheric Pressure	[kPa]	Specific Growth Area	[m^2/CM]	Water In-/Output	[kg/(m^2*d)]
	Pressurized Volume	[m^3]	CO_2 Partial Pressure	[kPa]	Growth Height	[m], [m/m^2]	CO_2 Intake	[kg/(m^2*d)]
	Specific Cultivation Volume	[m^3/m^3]	O_2 Partial Pressure	[kPa]			O_2 Output	[kg/(m^2*d)]
	Complexity						Crew Size	Number
							Crew Work Load	[h/(m^2*d)]
							Psychological Health Care	Procedure

4 Demonstration of the Developed Evaluation Strategy

In this chapter a survey of existing greenhouse concepts is accomplished in the first subchapter. Three of these concepts are selected for further investigation. The second subchapter describes the goal of the demonstrated evaluation. The third subchapter establishes the evaluation criteria and the local and global weighting values for each criterion. In the fourth subchapter the weighted evaluation criteria are used in an AHP to evaluate the selected concepts.

4.1 Description and Analysis of Selected Concepts and Testbeds

4.1.1 Survey on Existing Greenhouse Concepts

One of the common definitions of a greenhouse can be found in reference [**52**]: “A greenhouse has one purpose: to provide and maintain the environment that will result in optimum crop production or maximum profit. This includes an environment for work efficiency as well as for crop growth.” This statement defines the purpose of terrestrial and space greenhouses correctly. However, plant cultivation systems for space applications can differ from the above mentioned definition. Systems for plant cultivation in space are broadly divided into plant growth chambers (PGC) and greenhouse modules (GHM).

Plant Growth Chambers are usually systems with a small cultivation area of less than one square meter. The main purpose of today’s PGCs is the research of plant development and growing in a controlled environment under micro gravity. Other purposes of these chambers is the testing and verification of subsystems in space, the interaction between crew members and plants, and the psychological effect of plants in a sterile, highly technical environment. The plants cultivated in PGCs can be edible and inedible, depending on the purpose. However, the amount of produced edible biomass is generally low and can only be used as an addition to the normal food. Table 4-1 shows a list of some plant growth chambers and their key parameters.

Greenhouses are large systems or even independent modules of space stations or planetary habitats. The purpose of a GHM is the provision of edible biomass to the crew to reduce the required resupply mass of food. Depending on the mission requirements and the system design, GHMs can produce different sets of crops ranging from fresh vegetables for short duration missions over energy food for medium duration missions up to quasi-full nutrition for long duration missions or permanent planetary habitats. Furthermore, GHMs can be used as part of the ECLSS. The plants of a GHM can purify water, revitalize air and recycle some of the bio waste of the crew. As shown in Chapter 2.3 BLSS and therefore, GHMs are required for long duration and permanent extraterrestrial human settlements.

The variety of GHM concepts and test facilities is high. They can to be divided depending on their purpose and location into the four groups:

- Terrestrial plant cultivation test facilities,
- Terrestrial human isolation test facilities,
- Arctic and Antarctic plant cultivation test facilities,
- Greenhouse module concepts for space application.

Terrestrial plant cultivation test facilities are designed to research plant cultivation in a controlled environment on Earth. Research in plant growing and subsystem development are the major purposes of these facilities. Table 4-2 shows a selection of terrestrial plant cultivation test facilities and their properties.

Terrestrial human isolation test facilities are built to test ECLSS, the influence of isolation on the human psyche, and the interaction between humans in a highly technical environment. Some of these facilities include greenhouses for the provision of food to the test subjects. Usually, the design of these greenhouses is similar to that of greenhouse modules concepts for space application. Table 4-3 provides information about four human isolation test facilities with an integrated greenhouse.

Arctic and Antarctic plant cultivation test facilities are usually part of research outposts. They are used to provide fresh food during the winter periods, when resupply with aircraft is mostly impossible. For the maximization of yield some of these facilities are designed similar to space greenhouse modules. Another purpose of these facilities is the testing of remote controlling systems. Table 4-4 shows two famous Arctic respectively Antarctic greenhouses and their properties.

A large number of *greenhouse module concepts for space application* are published and nearly every concept of an extraterrestrial habitat includes a greenhouse module. However, most of these concepts are greenhouse designs without any scientific background and some of them are not even feasible due to structural or agricultural deficits. Only a small number of the published greenhouse module concepts are undergone a detailed scientific investigation with comprehensible assumptions and estimations. Table 4-5 shows two of these concepts including some of their properties.

For the following demonstration of the developed analysis and evaluation methodology, only GHMs are taken into account. Out of the list of terrestrial testbeds and conceptual greenhouse module designs, three concepts are selected for the demonstration. The Lunar Greenhouse (LGH), the Lunar Food and Revitalization Module (Lunar FARM) and the Biomass Production Chamber (BPC) of the Bioregenerative Planetary Life Support Systems Test Complex (BIO-Plex) are the candidates for the demonstration of the proposed analysis and evaluation methodology. A detailed description and analysis of each selected concept is provided in the following three subchapters. The selected concepts respectively test facilities are part of different groups of GHMs. However, all of them share enough similarities for an evaluation using the proposed methodology.

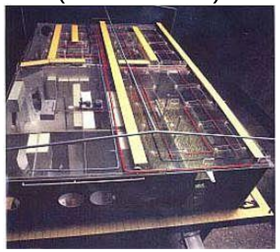
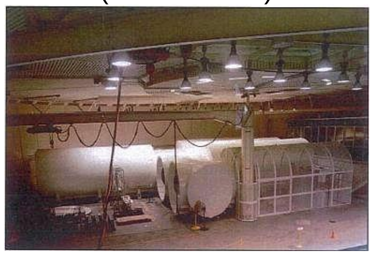
Table 4-1: List of flown plant growth chambers [53]

	Plant Growth Unit (PGU)	Astroculture (ASC)	Plant Growth Facility (PGF)	MIR Plant Growth Facility (SVET)	Plant Generic BioProcessing Apparatus (PGBA)	Biomass Production System (BPS)	Commercial Plant Biotech-nology Facility (CPBF)
Developer	Lockheed	WCSAR	A.D. Little	Bulgaria, Soviet Union	BioServe Space Technologies	Orbitec	WCSAR
First Flight	1982	1992	1997	1990	1996	> 1999	> 2000
Chamber Dimensions [m]	0.18 x 0.04 x 0.23	0.10 x 0.10 x 0.18	0.18 x 0.04 x 0.23	0.15 x 0.51 x 0.31	0.25 x 0.31 x 0.31	0.15 x 0.18 x 0.15	0.48 x 0.46 x 0.46
Total Growing Area [m^2]	0.050	0.021	0.055	0.075	0.075	0.027	0.2
Plant Chambers	6	1 – 2	6	1	1	1, 2 or 4	1 - 4
Temperature Control	None	TEC	TEC	None	TEC	TEC	TEC
Humidity Control	None (Sealed)	TEC	Passive	None	TEC / dew point	TEC / dew point	TEC / dew point
Light Intensity (PPF) [µmol/(m^2*s)]	60	300	220	240	> 350	300	500
Light Source	Fluorescent	LED (red + blue)	Comp. Fluorescent	Fluorescent	Comp. Fluorescent	Fluorescent	LED
Chamber Closure	Closed	Closed	Open	Open	Closed	Closed	Closed
Active CO_2 Control	Some	Yes	Some	No	Yes	Yes	Yes
CO_2 Range [ppm]	ambient	300-2000	ambient	5000 ppm	250 – 3000	300 – 2000	300 - 2000
Trace Gas Control	None	Yes	None	None	Yes	Yes	Yes
Root Matrix	Saturated foam, or agar	Porous rubes with matrix	Saturated foam, or agar	Zeolite / Balkanite	Agar or soil aggregate with wicking matrix	Porous tubes with matrix	Porous tubes with matrix
Nutrient Delivery System	None	Closed circula-tion loop	None	MIR Space Station water supply	Humidity condensate recycling	Closed loop	Closed loop

Table 4-2: List of terrestrial plant cultivation test facilities

Terrestrial Test Facility	Organization	Research Focus	Greenhouse Parameter		References
CLESS Experimental Facility (Since 2004) 	Department of ECLSS, China Astronaut Research & Training Center (Beijing, China)	Plant cultivation in closed loop & plant-human integrated experiments.	Total Cultivation Area	8.4 m²	[**54**]
			Temperature	15 – 40 °C	
			Relative Humidity	65 – 85 %	
			CO_2 Concentration	350 – 10000 ppm	
			Total Pressure	Earth-Like	
			Lighting	LED (95 % red, 5 % blue)	
			PPF	0 – 500 µmol/(m^2*s)	
			Growth Medium	Hydroponic	
Biomass Production Chamber (1988 – 1996) 	NASA Kennedy Space Center (Florida, USA)	Provides an unique opportunity to learn about the mass and energy flow though the CELSS along with the environmental needs for plant growth in a concealed environment.	Total Cultivation Area	20 m²	[**55**], [**56**], [**57**]
			Temperature	23 °C	
			Relative Humidity	70 – 80 %	
			CO_2 Concentration	1000 – 1200 ppm	
			Total Pressure	Earth-Like	
			Lighting	96x 400 W HID Lamps	
			PPF	200 – 700 µmol/(m^2*s)	
			Growth Medium	Hydroponic	
Lunar Greenhouse (Since 2005) 	Controlled Environment Agriculture Center, University of Arizona & Sadler Machine Company (Tucson, Arizona, USA)	Demonstration of maximum biomass generation and food production within a polyculture deployable cropping system. Furthermore, complete water recycling and revitalization of interior atmosphere.	Total Cultivation Area	8.8 m²	[**58**], [**59**]
			Temperature	21.1 °C	
			Relative Humidity	53.5 %	
			CO_2 Concentration	1000 ppm	
			Total Pressure	Earth-Like	
			Lighting	6x 1000 W HPS	
			PPF	300 – 400 µmol/(m^2*s)	
			Growth Medium	Hydroponic	

Table 4-3: List of terrestrial human isolation test facilities including a greenhouse

Human Isolation Test Facility	Organization	Research Focus	Greenhouse Parameter		References
Closed Ecology Experiment Facilities (Since 1994) 	Institute for Environmental Sciences (Rokkasho, Japan)	Designed to study the effects of material circulation mechanisms on the environmental factors prevailing within a closed ecosystem whose results can be used critically in designing systems for Lunar and Martian bases.	Total Cultivation Area	150 m²	[**60**], [**61**], [**62**], [**63**], [**64**], [**65**]
			Temperature	18 – 30 °C	
			Relative Humidity	50 – 90 %	
			CO_2 Concentration	700 – 5000 ppm	
			Total Pressure	Earth-Like	
			Lighting	108x 940 W HPS; Sun	
			PPF	up to 1900 µmol/(m^2*s)	
			Growth Medium	Hydroponic	
BIOS-3 (1972 – 1984) 	Russian Academy of Sciences (Kraznoyarsk, Russia)	The purpose of Bios-3 was the development of life support systems capable of supporting a crew of two to three persons with clean water, fresh air and a sufficient amount of food.	Total Cultivation Area	63 m²	[**66**], [**67**], [**68**], [**69**]
			Temperature	22 – 28 °C	
			Relative Humidity	70 – 80 %	
			CO_2 Concentration	2000 ppm	
			Total Pressure	Earth-Like	
			Lighting	20x 5 kW Xenon Lamps	
			PPF	900 – 1000 µmol/(m^2*s)	
			Growth Medium	Hydroponic, Inert Subs.	
Bioregenerative Planetary Life Support Systems Test Complex (1990s - 2001) 	NASA Johnson Space Center (Houston, Texas, USA)	Designed as test facility for human isolation experiments and as a testbed for life support systems. Food production, water purification and air revitalization and other key elements of an ECLSS can be evaluated during long duration experiments.	Total Cultivation Area	82.4 m²	[**70**], [**32**], [**71**]
			Temperature	15 – 35 °C	
			Relative Humidity	65 – 85 %	
			CO_2 Concentration	300 – 10000 ppm	
			Total Pressure	Earth-Like	
			Lighting	384 HPS Lamps	
			PPF	n/a	
			Growth Medium	Hydroponic	

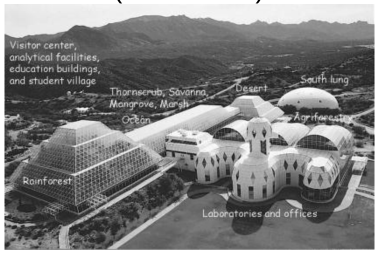
Biosphere 2 Intensive Agricultural Biome (Since 1986) 	Biosphere Foundation, University of Arizona (Tuscon, Arizona, USA)	The purpose of Biosphere 2 was the construction of human controlled mesocosm. Therefore, seven biomes with different layouts and climates were established. Furthermore, a human habitat was included in the facility to support a crew of ten.	Total Cultivation Area	2200 m²	[**72**], [**73**], [**74**], [**75**], [**76**]
			Temperature	13 – 30 °C	
			Relative Humidity	n/a	
			CO_2 Concentration	350 – 2000 ppm	
			Total Pressure	Earth-Like	
			Lighting	196x 1000 W HPS, Sun	
			PPF	n/a	
			Growth Medium	Terrestrial Soil	

Table 4-4: List of Arctic and Antarctic plant cultivation test facilities

Arctic & Antarctic Facilities	Organization	Research Focus	Greenhouse Parameter		References
Arthur Clarke Mars Greenhouse (Since 2002) 	Canadian Space Agency, University of Guelph, University of Florida (Haughton Mars Project Research Station on Devon Island, Canada)	The purpose of the ACMG is the studying of greenhouse engineering, plant growth and autonomous functionality under extreme operational conditions.	Total Cultivation Area	≈ 4 m²	[**77**], [**78**], [**79**]
			Temperature	15 – 30 °C	
			Relative Humidity	20 – 80 %	
			CO_2 Concentration	n/a	
			Total Pressure	Earth-Like	
			Lighting	Direct Natural	
			PPF	339 µmol/(m²*s) [in June]	
			Growth Medium	Hydroponic, Inert Subs.	
Amundsen-Scott - South Pole Food Growth Chamber (Since 2004) 	United States Antarctic Program	Bio regenerative life support systems research along with food support from crew and other psychological benefits.	Total Cultivation Area	21.9 m²	[**80**]
			Temperature	19.3 – 23.6 °C	
			Relative Humidity	59.6 ± 4 %	
			CO_2 Concentration	1334 ppm	
			Total Pressure	68 kPa	
			Lighting	12x 1000 W HPS	
			PPF	425 µmol/(m²*s)	
			Growth Medium	Hydroponic	

Table 4-5: List of greenhouse module concepts for space applications

GHM for Space Application	Organization	Research Focus	Greenhouse Parameter		References
Lunar Food and Air Revitalization Module (2008) 	2nd International Master Course in Space Exploration and Development Systems (SEEDS) (Mt. Malapert, Lunar South Pole)	Designed as a plant growth chamber module to be integrated into the Bio regenerative life support systems for a Lunar Mission.	Total Cultivation Area	144 m²	[**31**], [**81**], [**82**]
			Temperature	17 – 28 °C	
			Relative Humidity	25 – 75 %	
			CO_2 Concentration	265 ppm	
			Total Pressure	75.5 kPa	
			Lighting	Indirect Natural, HPS	
			PPF	n/a	
			Growth Medium	Hydroponic	
Autonomous Garden Pod (2002) 	NASA Mars Port Competition, University of Colorado (Colorado, USA)	Designed as inflatable plant growth chamber module to be integrated into the Bio regenerative life support systems for a Martian Mission.	Total Cultivation Area	9.9 m²	[**83**]
			Temperature	n/a	
			Relative Humidity	n/a	
			CO_2 Concentration	CO_2 rich atmosphere	
			Total Pressure	n/a	
			Lighting	Direct, Indirect Natural	
			PPF	n/a	
			Growth Medium	n/a	

4.1.2 Lunar Greenhouse

The Lunar Greenhouse (LGH) is a BLSS concept developed by an U.S.-Italian corporation under the leadership of the University of Arizona's Controlled Environment Agriculture Center (UA-CEAC). Other partners are Sadler Machine Company, Thales Alenia Space-Italia, Aero-Sekur, and the University of Naples Federico II. The project started in 2005 with a feasibility study and is still running. According to reference [**58**], the purpose of the Lunar Greenhouse project is the demonstration of biomass and food production, air and water revitalization, and waste recycling within a poly-culture deployable cropping system.

The module is designed to meet the requirements for a lunar science outpost established by NASA's Global Exploration Strategy. This scenario proposes a lunar outpost with four LGH modules at the Aitken Basin near the Lunar South Pole for a 4-person crew and mission duration of 180 days. The aim of the greenhouse for this scenario is full water purification and air revitalization, and the provision of up to 50 % of the required daily energy intake of the crew. The greenhouse module concept discussed in this chapter is able to fulfill these requirements for one human. Consequently, four modules are required to meet the requirements for the lunar outpost scenario [**58**].

The module consists of a deployable aluminum structure and has a cylindrical shape. Figure 4-1 shows a prototype of the LGH in folded configuration, while Figure 4-2 illustrates the module fully deployed and operational during a test phase. For outer shell of the module a fluorocarbon based polymer membrane is used. Due to the absence of a rigid outer shell, the module has to be covered with one meter of lunar soil to prevent the plants against the cosmic radiation. While deployed, the LGH has a length of 5.5 meters and a diameter of 2.06 meters. Consequently, the pressurized volume is around 21 cubic meters [**58**].

Figure 4-1: Folded Configuration of the LGH [59**]**

Figure 4-2: Deployed Configuration of the LGH during a test period [59**]**

The growth area is accommodated in two one-level shelves, one at each side of the centered aisle. The overall cultivation area of one module is around 8.8 square meters. When the aisle is also be used as growth area, 11.1 square meters growth area are available. The available growth height depends, due to the cylindrical shape, on the distance to the outer shell. The plants are grown in a hydroponic cultivation system. Different plant species were grown during several test phases, e.g. lettuce, strawberry and sweet potato. The developer of the LGH proposes a polycultural plant mixture to increase the variety of available food [**59**]. However, the plant selection for the lunar outpost scenario is based on reference [**23**].

The LGH is pressurized with 62 kilopascals. Thereby, the partial pressure of oxygen is maintained around 21 kilopascals and the atmosphere is enriched with carbon dioxide, leading to a CO_2 partial pressure around 0.062 kilopascals. Average environmental conditions, 21.1 degrees Celsius and 53.5 % relative humidity, are maintained inside the LGH. The lighting system solely consists of electrical lighting. Six high pressure sodium lamps with 1000 watts each are selected as light sources [**58**].

As described earlier, one LGH module is able to fully purify the used water and air of one human, while providing 1000 kilocalories per day. The waste generated by the harvested inedible biomass is treated in a separate composter module, which is currently under development. No crew work load values required for the maintenance of a LGH are published until now [**59**].

Appendix 3-1 shows the Morphological Box of the LGH concept, in which all available data about options and values is highlighted in green and factors with insufficient data are highlighted in orange.

4.1.3 Lunar Food and Revitalization Module

The Lunar Food and Revitalization Module (Lunar FARM) is the result of a feasibility study accomplished during the 2nd International Master Course in Space Exploration and Development Systems (SEEDS) in 2008. The aim of the study was to design a Permanent Human Moon Exploration Base (Phoebe). Phoebe should be located on top of Mount Malapert at the Moon’s South Pole. The advantage of this location is the nearly continuous coverage with sunlight: 89 % per year direct sunlight and 4 % of the year partial illumination due to the Sun [**81**].

During the feasibility study an inflatable, a hybrid and a rigid structural design were considered. Finally, the rigid design was proposed for the FARM, because of its advantages concerning outfitting and system preparation. The final design is a cylindrical module with a diameter of eight meters and a length of twelve meters. Figure 4-3 shows the outside view of one Lunar FARM. Inside the module are two floors for the cultivation of plants and the related subsystems, each floor has a height of 2.5 meters and is six meters wide, see Figure 4-4. The floors are connected with an elevator and emergency stairs. According to reference [**31**], the estimated mass of one module is around 8000 kg.

The growth area is accommodated in shelves. The proposed internal configuration consists of three aisles and four rows of shelves, as shown in Figure 4-4. Each shelf has four levels, two with a height of 65 centimeters and two with a height of 45 centimeters. Thereby, the lowest level is used for holding subsystems or germination units, while the other three are used for the cultivation of plants. The lower 15 centimeters of each level are reserved for the growth medium and root zone. Consequently, there are two shelf levels for plants with a growth height up to 50 centimeters and one level for plants with a growth height up to 30 centimeters. The overall growth area of one FARM is 144 square meters, 96 square meters for plants up to 50 centimeters high and 48 square meters for plants up to 30 centimeters high. All plants are grown hydroponically [**31**].

Figure 4-3: Outside view on the Lunar FARM [31**]**

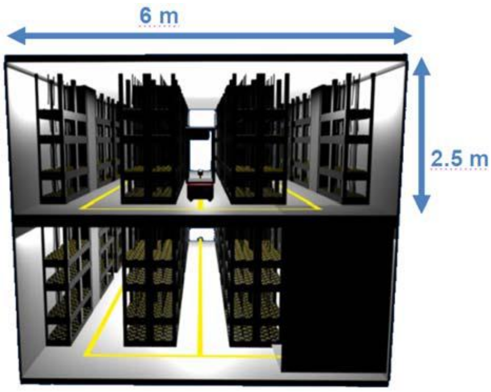


Figure 4-4: Cross section view of the Lunar FARM [31**]**

Different concepts of plant diversity were investigated during the study. Finally, an energy food plant composition was selected, which can provide 84 %, 1753 kcal per day per crew-member, of the crew's daily energy intake. Consequently, 16 % of the required food has to be supplied from Earth frequently. Beans, carrot, green onion, pepper, white potato, straw-berry, tomato and wheat were selected for the cultivation inside the FARM. The selected food plants cause deficiencies in vitamin B12, vitamin E, calcium and sodium. Consequently, the food supplied from Earth has to compensate these deficiencies. The growth area per plant species is not published, but Table 4-6 shows the expected output of edible biomass of one module per plant species per day [**82**].

Table 4-6: Daily expected production of edible biomass per plant species per module, derived from [31**]**

Plant Species	Beans	Carrot	Green Onion	Pep-per	White Potato	Straw-berry	Toma-to	Wheat
Food Output [kg/day]	1.68	1.68	1.13	1.13	1.13	0.85	1.68	1.68

The atmospheric pressure inside the greenhouse module is supposed to be 75.5 kilopascals, with an oxygen partial pressure of 21.1 kilopascals. The carbon dioxide partial pressure is maintained at 0.02 kilopascals. The temperature inside the FARM ranges from 17 to 28 degrees Celsius, while the relative humidity is hold between 25 and 75 %. The study team proposes a hybrid lighting system consisting of an indirect natural system as the primary radiation source and high pressure sodium lamps as secondary system. As discussed earlier, the location of Phoebe is under direct sunlight for the most time of the year. The natural lighting system consists of parabolic concentrators which feed an optic fiber distribution system. The concentrator is always pointed sunwards and focusses the incoming radiation to a collecting mirror. This mirror directs the light into the optic fiber network. The optic fibers deliver and distribute the light to all plants of the module. For dark periods high pressure sodium lamps are implemented to keep the plants alive. The overall power consumption of the lamps is restricted to four kilowatts. The HPS lamps feed the optic fiber network. Consequently, an appropriate light distribution can be maintained [**81**].

The FARM was designed to grow food plants for the nourishment of Phoebe's crew. The proposed crew composition is 50 % men and 50 % women and a permanent crew size of 18 people. Furthermore, during crew exchange six additional humans will live in Phoebe for 14 days. The crew exchange was supposed to be every eight weeks. In addition to the crew exchange, six visitors will stay at the base for seven days every eight weeks. However, crew exchange and visiting should never overlap, which leads to a maximum crew size of 24. For the provision of food to the desired crew size four FARMs are required. Besides the plant cultivation the FARM is used to purify the water and revitalize the air of the whole habitat. The water output is estimated to be around 36 kilograms per day and the amount of generated oxygen is calculated to 1.0 kg per crewmember per day. To maintain all functions of one module and to grow and harvest the desired amount of food, reference [**31**] assumes a workload of ten man-hours per day for the whole module. Consequently, the crew work load is around 0.07 man hours per square meter per day.

Appendix 3-2 shows the Morphological Box of the Lunar FARM concept, in which all available data about options and values is highlighted in green and factors with insufficient data are highlighted in orange.

4.1.4 Biomass Production Chamber of BIO-Plex

The Bioregenerative Planetary Life Support Systems Test Complex (BIO-Plex) is one of NASA's projects of the Advanced Life Support (ALS) program and is located at the Johnson Space Center (JSC) in Houston. BIO-Plex is designed as test facility for human isolation experiments and as a testbed for life support systems. Systems regarding the food production, water purification and air revitalization and other key elements of an ECLSS can be integrated and evaluated during long duration experiments. The purpose of BIO-Plex is the provision of a closed environment including a small crew for the testing of current and future regenerable systems technologies. The design of the facility began in the early 1990s, but the project was directed to suspend ongoing activities in 2001 due to the declining NASA budget. Since 2001 the built parts of the facility are placed in a "stand-by" mode. [**70**].

BIO-Plex consists of six cylindrical chambers and an airlock connected to an interconnecting tunnel. Figure 4-5 shows an outside view on BIO-Plex during the integration. The transparent airlock is attached on the right side, while two modules on the left side are still missing. Each of the six chambers has a different purpose. The habitation chamber accommodates the crew quarters. The life support chamber contains all systems required to maintain the desired environmental conditions, while the utilities distribution module serves as storage room for tools. A laboratory chamber is proposed for a later development stage of the complex. Furthermore, BIO-Plex has two Biomass Production Chambers (BPC). Hence, the BPC design is described in detail in the following [**32**].

The BPC has a rigid cylindrical structure as every chamber of BIO-Plex, is 11.3 meters long and has a diameter of 4.6 meters. Consequently, the BPC has a pressurized volume of 187.8 cubic meters. Most of the crop processing systems are located inside the interconnecting tunnel. Consequently, a wider door, 168 centimeters, compared to the other chambers is installed between the BPC and the interconnecting tunnel, which facilitates an easier handling of seedlings, plants and harvested crops [**32**].

The growth area is accommodated in shelves. Therefore, four shelf designs were considered during the design process. Finally, a two aisles three shelves configuration was selected as shown in Figure 4-6, each shelf has a length of 9.1 meters. The two outer shelves have three levels each. The top level is 37.5 centimeters wide and provides a maximum growth height of 44 centimeters. The middle level is 72 centimeters wide and the maximum growth height is 70 centimeter. The bottom level provides a width of 37.5 centimeters and a maximum growth height of 40 centimeters. Consequently, one outer shelf contains an available growth area of 3.3 square meters in the top and bottom level and 6.2 square meters in the middle level. The center shelf consists of four identically sized levels. Each is 150 centimeters wide and provides a growth height of up to 50 centimeters, which leads to a growth area of 14.2 square meters per level. Hence, the overall growth area of the BPC is 82.4 square meters large. A hydroponic cultivation system is established for the growing of plants. However, it is also feasible to use soil-like substrates as growth medium when necessary [**32**].

Figure 4-5: Outside view on Bio-Plex during integration [70**]**

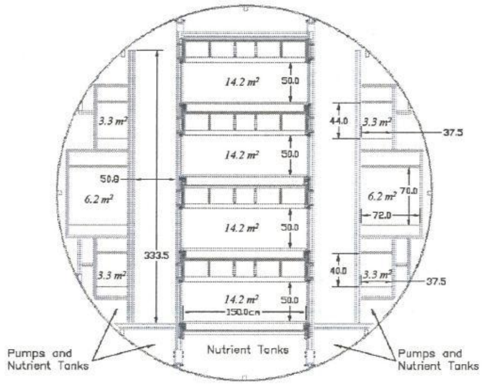


Figure 4-6: Cross section view of the BPC of Bio-Plex [32**]**

The BPC is designed to serve as a quasi-full nutrition source for the crew. Consequently, fresh and energy food plants are grown. The allocated growth area per plant species is not published. Storable crops like wheat, rice, white potato, sweet potato, soybean, peanut and beans are batch planted, while fresh crops like lettuce, cabbage, spinach, chard, carrot, radish and onion are staggered planted [**32**].

The atmospheric pressure inside the BPC is maintained at the terrestrial ambient level outside of BIO-Plex. The oxygen partial pressure is sustained between 20 and 24 kilopascals, while the carbon dioxide partial pressure can be adjusted in the range from 0.03 to 1.0 kilopascal. However, at carbon dioxide concentrations above 0.4 kilopascals human entry to the BPC will be prohibited. The temperature can be adjusted to every shelf level individually from 15 to 25 degrees Celsius during dark periods and from 16 to 35 degrees Celsius during light periods. Relative humidity can be solely controlled for every shelf level between 65 and 85 %. The design of the BPC's lighting system is flexibly adjustable. Each shelf level is split into three sections, which contain four light boxes. The proposed configuration consists of eight high pressure sodium lamps per light box. However, due to the flexible design the light boxes can also be outfitted with optic fiber cables to facilitate indirect natural lighting [**32**].

BIO-Plex is designed to house four humans and therefore, the BPC can provide enough food for the crew. The plants cultivated in the BPC are used for water purification and air revitalization. However, no values for the water in-/output, the carbon dioxide intake or the oxygen output are published until now. Furthermore, no data about the required crew work time is available. Due to the high level of automation, it can be assumed that the work load is relatively low [**32**].

Appendix 3-3 shows the Morphological Box of the BIO-Plex concept, in which all available data about options and values is highlighted in green and factors with insufficient data are highlighted in orange.

4.2 Goal Definition for the Exemplary Evaluation

The goal of the exemplary evaluation in the following subchapters is the comparison of the three previously selected concepts with a hypothetically optimal greenhouse module. The characteristics of this optimal greenhouse module are based on the definition of measurable factors presented in Chapter 3.4. Table 4-7 shows a list of all established factors with the requirements an optimal greenhouse has to fulfill.

The shape, the dimensions, the total mass and the total volume of an optimal greenhouse module are restricted by the available launch systems. Consequently, the specific cultivation volume must be as high as possible to reduce the specific module mass. A shelf configuration similar to the presented two aisles three shelves arrangement, see Figure 3-9, can provide a high specific cultivation volume. The complexity of an optimal greenhouse module is as low as possible. For cost reduction reasons, the pressurized volume has to be as small as possible. The module structure should be made out of in-situ materials to reduce the total mass of the module. The internal configuration has to be flexibly adaptable to different plant setups. A high level of automation is necessary to reduce the required work load of the crew.

The lighting is an essential part of greenhouse modules. An optimal greenhouse module would use indirect natural lighting. When natural lighting is not available, LEDs are the most promising electrical lighting devices. Intracanopy lighting is the most effective light distribution strategy. The atmosphere in the plant cultivation volume has to be enriched with CO_2 to maximize the yield. Another increase in yield can be achieved by controlling the temperature of each growth unit separately. Monitoring and separation of trace gases is indispensable. The photosynthetic period, humidity, temperature, CO_2 and O_2 concentration, and the atmospheric pressure have to fit the optimal conditions of the cultivated plants.

Hydroponic agriculture is the most promising cultivation method. In an optimal greenhouse module the plants are grown in monocultures and depending on the plant species they are planted staggered or as batches. Nutrients have to be recycled and produced out of inedible biomass and bio waste. Plant monitoring for every growth unit is necessary to control the development of the plants. The selected plants have to meet the requirements of a quasi-full nutrition. The module has to provide the required growth height for every cultivated plant species. The total growth area and the biomass productivity have to be as high as possible.

An optimal greenhouse module is a high efficient plant cultivation system, which provides a quasi-full nutrition to the desired amount of crew members. Furthermore, the greenhouse module should be able to fully revitalize the air and water consumed respectively processed by the crew. The power and consequently, the cooling demand of an optimal greenhouse module have to be as low as possible to reduce the required amount of electrical energy. The crew work load required for the cultivation of plants and the maintenance of all greenhouse subsystems should be as low as possible. In addition an optimal greenhouse module would actively enhance the psychological health of the crew.

Table 4-7: Requirements for an optimal greenhouse regarding the established measurable factors

Fundamental Factors	Requirement	Environmental Factors	Requirement
Module Shape	Restricted to available launch systems	Lighting Type	Indirect natural lighting, respectively LED lighting
Arrangement of Growth Area	Shelves	Lighting Strategy	Intracanopy
Distribution of Aisles	Two aisle three shelves option	Atmospheric Composition	Enriched with CO_2
Module Structure	In-Situ	Trace Gas Treatment	Monitoring and Separation
Adaptability of internal Configuration	Flexible	Temperature Control	Per Growth Unit
Level of Automation	Full	Photosynthetic Period	Optimal for the cultivated plants
Specific Module Mass	As low as possible	Humidity	Optimal for the cultivated plants
Total Module Mass	Restricted to available launch systems	Air Temperature	Optimal for the cultivated plants
Dimensions	Restricted to available launch systems	Atmospheric Pressure	As low as suitable for plant cultivation
Total Volume	Restricted to available launch systems	CO_2 Partial Pressure	Optimal for the cultivated plants
Pressurized Volume	As small as possible	O_2 Partial Pressure	As low as suitable for plant cultivation
Specific Cultivation Volume	As large as possible		
Complexity	As low as possible		
Agricultural Factors	**Requirement**	**Interface Factors**	**Requirement**
Growth Medium	Hydroponic	Water Purification	Full
Nutrient Supply	Full recycling	Air Revitalization	Full
Plant Monitoring	Per growth unit	Resupply Dependency	Quasi-full nutrition
Plant Mixture	Monoculture	Food Provision	2200 kcal/(CM*d)
Planting Sequence	Combined	Power Demand	As low as possible
Biomass Productivity	As high as possible	Cooling Demand	As low as possible
Cultivated Plants	Plants for a quasi-full nutrition	Water In-/Output	As high as possible
Total Growth Area	As high as possible	CO_2 Intake	Suitable for the desired crew size
Specific Growth Area	As low as possible for a quasi-full nutrition	O_2 Output	Suitable for the desired crew size
Growth Height	Optimal for the cultivated plants	Supported Crew Size	As high as possible for a quasi-full nutrition
		Crew Work Load	As low as possible
		Psychological Health Care	As much as possible

4.3 Establishing and Weighting of Evaluation Criteria

This subchapter describes the process of selecting evaluation criteria out of the list of analysis and evaluation factors established in Chapter 3.4. Furthermore, the calculation of all local and global weighting values for an AHP evaluation is explained.

4.3.1 Selection of Evaluation Criteria

In Chapter 3.4 a comprehensive list of measurable factors is established, in total 46 factors were identified, as shown in Table 3-20. However, not all of these factors can be used as evaluation criteria for an AHP. Consequently, the factors can be divided into evaluation criteria and analysis parameters.

Analysis parameters are valuable for the analysis of concepts, but they cannot be used as evaluation criteria. Consequently, they are not established as criteria for the AHP. Nineteen factors can be defined as analysis parameters. They are highlighted in red in Appendix 4-1, which is a modified version of the previously introduced Morphological Box.

The remaining 27 factors are suitable evaluation criteria. However, due to a lack of data of the investigated concepts, not all criteria are used in the following AHP. Eleven evaluation criteria have to be rejected, because one or more of the three investigated concepts do not provide enough data for an evaluation. Appendix 3-1, Appendix 3-2 and Appendix 3-3 show the Morphological Boxes of the three concepts. The criteria with insufficient data provision are highlighted in orange in Appendix 4-1.

The selection process leads to sixteen suitable evaluation criteria with sufficient data provision by the three investigated concepts. These criteria are highlighted in green in Appendix 4-1. Finally, a hierarchy for the following AHP is generated out of the selected evaluation criteria. Figure 4-7 shows the established criteria hierarchy, which is based on the categorization of the measurable factors described in Chapter 3.4.1. Consequently, the criteria are grouped to the four categories: fundamental criteria, environmental criteria, agricultural criteria and interface criteria. These four categories form level 1 of the hierarchy, the inner ellipse of the Figure 4-7. Level 2 consists of the evaluation criteria themselves, whereby qualitative criteria are shown as ellipses and quantitative criteria are shown as rounded rectangles. Level 3, the large complete ellipse, consists of the possible options of the qualitative criteria and the concrete values of the investigated concepts for the quantitative criteria. For the Criteria growth medium and lighting type, an additional level is required. Consequently, the options are on level 4 of the hierarchy.

The established hierarchy is used as the framework for the calculation of local and global weightings of each criterion respectively option. The calculation is described in the following subchapter.

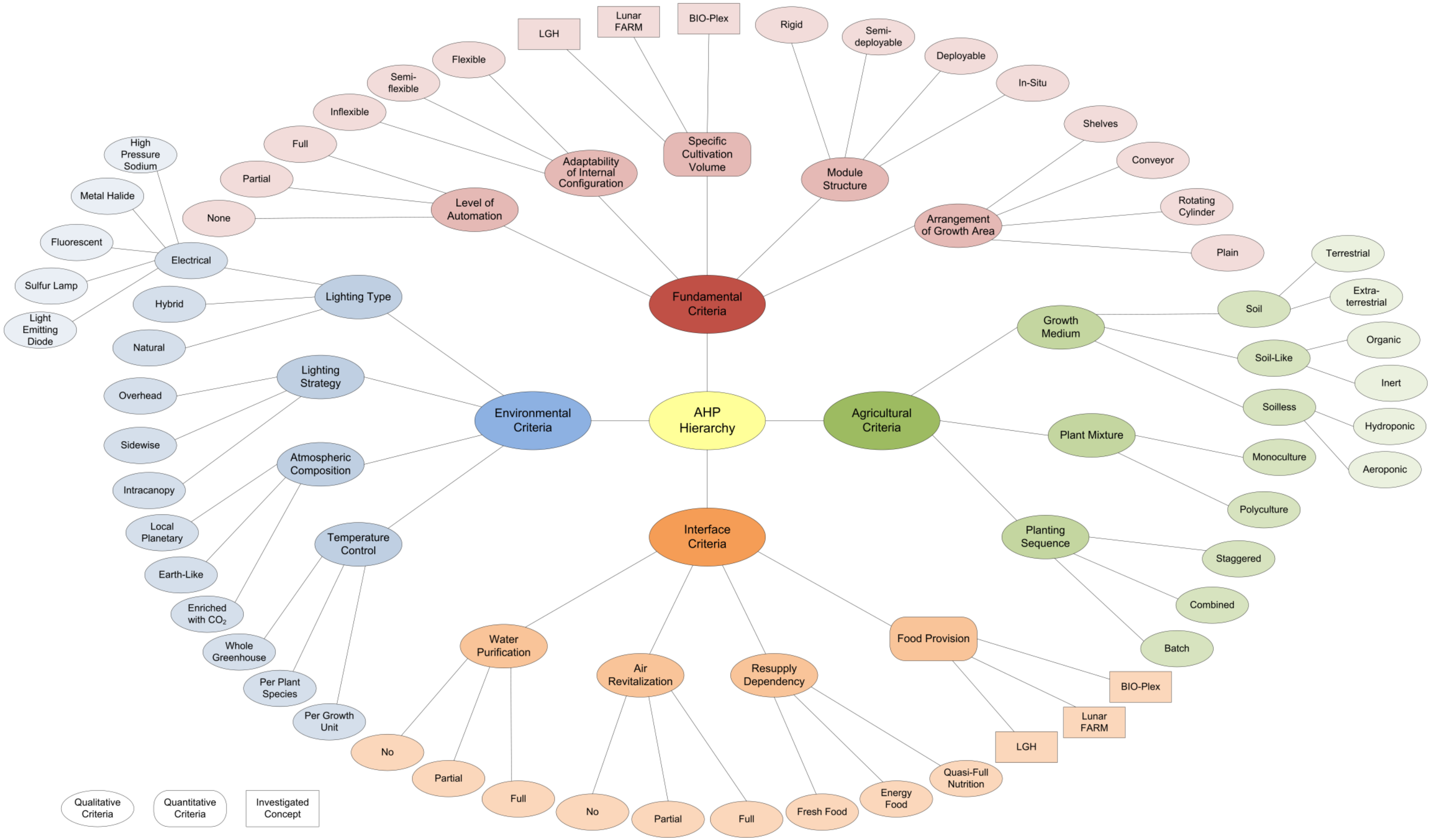


Figure 4-7: Hierarchy of the selected evaluation criteria (level 1 to level 4, from the inside to the outside)

4.3.2 Calculation of Local and Global Weightings

The calculation of local and global weightings for the selected evaluation criteria is based on the equations presented in Chapter 3.3.2. An Excel file is generated for the calculation which covers all pairwise comparisons, the calculation of weightings and the consistency check. Furthermore, the evaluation of the three selected greenhouse module concepts is also included in the Excel file. This subchapter shows an exemplary calculation and presents all resulting values for the local and global weighting of the selected criteria.

The weighting of the criteria is based on the goal of the demonstration of the developed analysis and evaluation methodology. The detailed goal definition is described in Chapter 4.2.

The pairwise comparisons are generally based on scientific background. However, the subjective opinion of the analyst affects the rating of the comparisons. Consequently, a small group of greenhouse experts working on the greenhouse project of the Institute of Space Systems of the German Aerospace Center (DLR) in Bremen was formed for the rating of the pairwise comparisons. The use of a small group of experts during an AHP is a suitable method to reduce the bias during the establishing of the pairwise comparisons. The group of experts consisted of the author of this thesis (graduate student in aerospace engineering), the DLR greenhouse project leader, a graduate student of biology and two other aerospace engineering graduate students. The final values for the pairwise comparisons are the results of negotiations and discussions between the five group members.

In the following the calculation of the local weightings of the four criteria categories on level 1 of the hierarchy is shown. The calculation process is same for all local weightings. Consequently, the shown calculation stands representatively for all local weighting calculations.

Level 1 of the AHP hierarchy consists of the four elements:

- Fundamental Criteria (FC),
- Environmental Criteria (EC),
- Agricultural Criteria (AC),
- Interface Criteria (IC).

The weighting calculation starts with the pairwise comparison of the four elements. Therefore, each element is compared one by one to each of the other elements. For the comparison the rating system shown in Table 3-3 is used. The result of the pairwise comparison is the comparison matrix. Table 4-8 shows the comparison matrix for the calculation of local weightings for level 1 of the hierarchy. Thereby, the values of the pairwise comparisons are inserted in the lower left part of the matrix, while the upper right half is the reciprocal of the lower left half. Consequently, environmental criteria have a strong importance over fundamental criteria, or the importance of environmental criteria is four times higher compared to fundamental criteria. Agricultural criteria have a moderate importance over fundamental criteria, but they are only half important as environmental criteria. The importance of interface criteria compared to fundamental, environmental and agricultural criteria is one third, one ninth and one fifth.

Table 4-8: Comparison matrix for the calculation of local weightings of hierarchy level 1

	Comparison Matrix			
	FC	**EC**	**AC**	**IC**
FC	1	0.250	0.333	3.000
EC	4.000	1	2.000	9.000
AC	3.000	0.500	1	5.000
IC	0.333	0.111	0.200	1
Σ Column	8.333	1.861	3.533	18.000

The values of the pairwise comparisons are then normalized by the sum of their related column. Afterwards, the normalized values are summed up row by row. The result is the normalization matrix shown in Table 4-9. Finally, the local weighting is calculated by dividing the sum of each row by the size of the matrix. In the shown example the matrix has a size of four.

Table 4-9: Normalization matrix and local weightings of hierarchy level 1

	Normalization					Weighting
	FC	**EC**	**AC**	**IC**	**Σ Row**	**w**
FC	0.120	0.134	0.094	0.167	0.515	**0.129**
EC	0.480	0.537	0.566	0.500	2.083	**0.521**
AC	0.360	0.269	0.283	0.278	1.189	**0.297**
IC	0.040	0.060	0.057	0.056	0.212	**0.053**
Σ Column	1.000	1.000	1.000	1.000	4.000	**1.000**

The exact local weightings for the four elements on level 1 of the hierarchy are:

- Fundamental Criteria = 0.12883,
- Environmental Criteria = 0.52084,
- Agricultural Criteria = 0.29736,
- Interface Criteria = 0.05297.

Consequently, the selected environmental criteria have the highest impact on the total weighting score of the investigated concepts, followed by the agricultural, the fundamental and the interface criteria.

The calculation of the local weightings is followed by the consistency check, in which the consistency of the pairwise comparisons is investigated. Therefore, the mean matrix is generated to calculate the Eigenvalue of each element of the matrix. Table 4-10 shows the mean matrix and the related Eigenvalues for each element.

The Eigenvalues are part of the calculation of the consistency relationship (CR), as described in Chapter 3.2. The CR value for the local weighting calculations of hierarchy level 1 is 0.014. The boundary value for consistency is 0.1, a CR smaller than the boundary value leads to a consistent pairwise comparison. Consequently, the pairwise comparisons of level 1 are consistent and therefore, the local weightings are reliable.

Table 4-10: Mean matrix for consistency check of local weighting calculation of level 1

	Mean Matrix					
	FC	**EC**	**AC**	**IC**	**Σ Row**	**λ**
FC	0.129	0.130	0.099	0.159	0.517	4.013
EC	0.515	0.521	0.595	0.477	2.108	4.047
AC	0.387	0.260	0.297	0.265	1.209	4.066
IC	0.043	0.058	0.059	0.053	0.213	4.026

The complete calculations of all local weighting values including the consistency check are shown in Appendix 4-1 to Appendix 4-27.

The local criteria weightings can be used to compare elements of the same hierarchy level and of the same parent category. To compare elements of the same hierarchy level, but of different parent categories, global weighting values are required. The global weighting of a certain criterion is calculated by multiplying the local weightings of the related parent categories. Table 4-11 shows the top 10 ranked options of hierarchy level 3 and 4. Therefore, an atmosphere enriched with CO_2 has the highest impact, followed by hydroponic cultivation and indirect natural lighting.

A summary of the local weightings of each hierarchy level and the global weightings of each possible option on level 3 and 4 are shown in Appendix 4-28. Consequently, the hypothetically optimal greenhouse module described in the goal definition for the demonstration of the methodology reaches the highest possible score by implementing the options with the highest global weightings compared to the other options of the same parent category.

Table 4-11: Top 10 ranking of quantitative criteria of level 3 and 4

Criterion Level 3/4	Global Weighting
Atmosphere Enriched with CO2	**0,11694**
Hydroponic Cultivation	**0,10827**
Indirect Natural Lighting	**0,09166**
LED Lighting	**0,05963**
Monocultural Cultivation	**0,05935**
Intracanopy Lighting Strategy	**0,05748**
Inert Soil-Like Growth Medium	**0,03652**
Hybrid Lighting	**0,03492**
Temperature Control per Growth Unit	**0,03241**
Combined Planting Sequence	**0,02916**

4.4 Evaluation of Selected Concepts and Testbeds

In this subchapter the results of the evaluation of the three selected greenhouse concepts described in Chapter 4.1 are presented. For the evaluation process the goal defined in Chapter 4.2 and the criteria selected and weighted in Chapter 4.3 are used in an AHP, as described in Chapter 3.3.2. Furthermore, an optimal greenhouse module concept regarding the criteria weighting is established for comparative reasons.

The *Lunar Greenhouse (LGH)* concept is described in detail in Chapter 4.1.2. Appendix 4-29 provides the detailed score for the evaluation of this concept. The revolutionary deployable design of the LGH is an advantage over the over two concepts. In addition, this concept has the highest specific cultivation volume of all evaluated concepts. However, the overall score is the lowest of the three investigated concepts, as shown in Table 4-12, due to many deficits. As a consequence of the proposed deploying mechanism, the internal configuration is inflexible and therefore, cannot be adapted for different purposes. The main reason for the low overall score are the deficits the environmental criteria category. Especially, the selected lighting type and lighting strategy, High Pressure Sodium Lamps respectively overhead lighting, are disadvantageous over other options. The control of the temperature is only possible for the whole greenhouse and not for separate sections. The maintained temperature is a compromise between the cultivated plant species. The proposed polycultural plant mixture is unfavorable compared to monocultural cultivation. The LGH is designed to grow fresh food. Consequently, the food provision is too low to provide a quasi-full nutrition for the crew.

The *Lunar Food and Revitalization Module (Lunar FARM)* concept has the highest total score of all three evaluated concepts. The total score of all investigated concepts is shown in Table 4-12. A detailed description of Lunar FARM is provided in Chapter 4.1.3 and the score of all criteria is listed in Appendix 4-30. The proposed internal configuration of the Lunar FARM is an arrangement of shelves, which are semi-flexible adaptable. However, the specific cultivation volume is low compared to the other concepts, because the space reserved for systems is relatively high. An optimization of the arrangement and system allocation can increase the specific cultivation volume. The major advantage of the Lunar FARM concept is the design of the environmental systems. Lunar FARM achieves the optimum in all four criteria of this criteria category. The lighting type is proposed to be mainly an indirect natural lighting system, with LEDs as a backup system for the short dark periods. The lighting is distributed to the plants via an intracanopy system of fiber optic cables. The temperature can be controlled for each plant growth unit separately and the atmosphere inside the units is enriched with carbon dioxide. The Lunar FARM concept is designed to provide energy food to the crew. Consequently, the food provision is lower than for a quasi-full nutrition. However, as described in Chapter 4.1.3, Lunar FARM can be used to grow plants for a quasi-full nutrition, when the work load can be reduced significantly.

The *Biomass Production Chamber (BPC) of the Bioregenerative Planetary Life Support Systems Test Complex (BIO-Plex)* is introduced in Chapter 4.1.4. The score of this concept for each criterion is shown in Appendix 4-31. The BIO-Plex concept is similar to the Lunar FARM concept. However, the total score of BIO-Plex is lower than that of Lunar FARM, as shown in Table 4-12. The internal configuration of BIO-Plex consists of an arrangement of shelves and the shelf configuration is similar to that of Lunar FARM. Nevertheless, the BPC of BIO-Plex has a higher specific cultivation volume. The deficits of this concept are in the environmental criteria category, due to the high weighting of this category, the deficits have a high impact.

The lighting system of the BPC consists of overhead mounted High Pressure Sodium Lamps. Lighting type and lighting strategy are not ideal and consequently, have a relatively low weighting. The proposed combined planting sequence is advantageous. The BPC of BIO-Plex is designed for quasi-full nutrition and therefore, the food provision per crew member nearly fits the human requirements.

The proposed *optimal design* for greenhouse modules is based on the weighting of evaluation criteria provided in Chapter 4.3. For this design only the options with the highest weighting score are selected. Consequently, the total score of the optimal design represents the highest possible score for this evaluation.

Table 4-12: Total score of the selected greenhouse module concepts

	LGH	Lunar FARM	BIO-Plex	Optimal Design
Total Score	0,31608	0,51336	0,45348	0,60430
Detailed Score	Appendix 4-29	Appendix 4-30	Appendix 4-31	Appendix 4-32

Figure 4-8 shows the comparison of the three evaluated concepts with the optimal concept with respect to every criterion. The criteria are grouped to their categories. As described above the LGH concept has the lowest total score of all concepts, because it achieves the optimum in only five out of sixteen criteria. The Lunar FARM concept has a higher score than the BPC of the BIO-Plex project, because Lunar FARM achieves the optimum in all four criteria of the environmental criteria category which has the highest local weighting factor of all four categories. Altogether, Lunar FARM reaches the optimum in nine criteria out of sixteen. However, the BPC of BIO-Plex achieves the optimum in ten criteria, but this concept has some deficits regarding the lighting system. Nevertheless, the BPC of BIO-Plex has the highest score in the agricultural criteria and interface criteria categories.

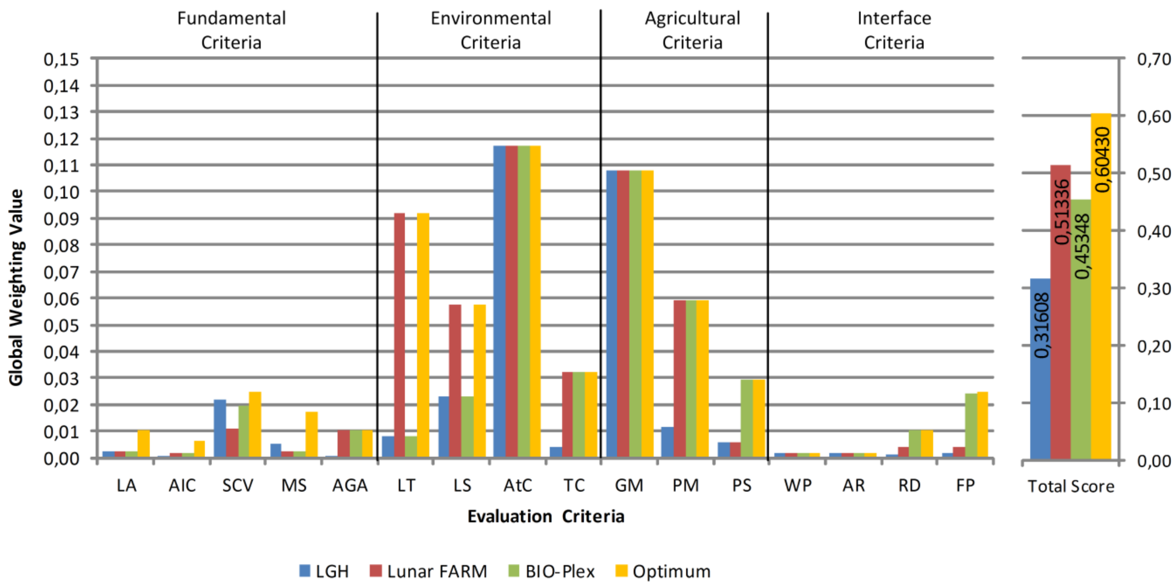


Figure 4-8: Comparison of the evaluated concepts with an optimal greenhouse concept

As described above, the concepts of the Lunar FARM and BPC are similar to each other in terms of structure and internal configuration. Consequently, a combination of the advantages of both concepts would lead to a nearly optimal greenhouse module concept.

4.5 Summary

Chapter 4 demonstrates the previously developed analysis and evaluation methodology. Therefore, a survey on existing greenhouse module concepts and test facilities is executed in the first subchapter. Out of the provided list of greenhouse modules, three concepts were selected for further investigation. All three greenhouses are analyzed in detail in the first subchapter.

The second subchapter defines the goal of the exemplary evaluation. A hypothetically optimal greenhouse module is established for the demonstration of the methodology. Therefore, the best options of the previously established evaluation factors are combined. The properties of the optimal greenhouse module are shown.

The third subchapter describes the selection process of the evaluation criteria. Depending on the available data of the selected concepts and the characteristics of the established factors, the evaluation criteria are selected. A hierarchy based on the factor categorization is created for the AHP evaluation. Furthermore, the local and global weightings for all elements of the hierarchy are calculated and checked on consistency. The calculation of the weightings is based on the previously defined goal of the evaluation. The values are calculated by the equations of the AHP described in Chapter 3.3.2 and are the results of the pairwise comparisons of the elements of the hierarchy.

The fourth subchapter utilizes the established criteria weighting for the evaluation of the three selected greenhouse module concepts. The Lunar Greenhouse (LGH) achieves the lowest score due to deficits regarding the environmental criteria. The Biomass Production Chamber (BPC) of the BIO-Plex facility has a high score in the agricultural criteria category. However, due to minor deficits in the environmental criteria category, especially the lighting system, the BPC of BIO-Plex achieves only the second highest score of all three concepts. The greenhouse module concept with the highest total score is the Lunar Food and Revitalization Module (Lunar FARM). Lunar FARM reaches the optimum in all subcriteria of the environmental criteria category, which has the highest influence. However, even the Lunar FARM concept has deficits compared to an optimal concept, especially, in the agricultural criteria category. Finally, a combination of the advantages of Lunar FARM and the BPC of BIO-Plex could achieve a score similar to the hypothetically optimal greenhouse module design.

5 Discussion

Terrestrial human isolation test beds like the Japanese Closed Ecology Experiment Facilities and the Russian BIOS-3 demonstrated the possibility of providing food with greenhouse modules to humans in a closed environment. Furthermore, the air revitalization and water purification with the use of the plants inside the greenhouse module worked well. Greenhouse modules as part of ECLSS of crewed spacecraft or habitats are necessary for future long term or even permanent missions to Moon and Mars.

Unfortunately, the prospects for utilization of greenhouse modules in a planetary mission in the near future are, at this stage, minimal. Neither NASA nor ESA have concrete plans for crewed long duration missions to planetary bodies in the near future. However, the today's research related to greenhouse modules is necessary, because of the not well understood relation between plants, humans and environmental conditions in closed ecosystems. This thesis lays a profound scientific background for the ongoing research activities at the DLR Bremen.

This thesis provides a comprehensive list of measurable factors. However, future researchers might think about adding their own factors, which is feasible due to the general nature of the selected analysis and evaluation methods. Consequently, the proposed methodology can be adapted to future evaluations by the analysts. This makes the analysis and evaluation strategy to a favorable tool for the investigation of developed greenhouse modules designs.

The selected evaluation criteria can be freely adapted to fit to the goals of future investigations of greenhouses. In addition the possibility of recalculating the criteria weighting exists and could be necessary for other evaluation goals. The generated Excel file can be used as tool for future calculations of criteria weightings.

However, for the defined goal of the exemplary evaluation of the selected greenhouses, the criteria weighting is reliable. This reliability can be guaranteed, because of the negotiation of a group of greenhouse researchers. The weightings himself are checked on consistency and no inconsistent weighting could be identified. The greenhouse concept with the highest score, the Lunar FARM, has a sophisticated design and the simulations executed during the design of this concept provide a good data source. Nevertheless, the evaluation showed, that even the Lunar FARM concept cannot match with the established hypothetically greenhouse design.

The relations between the measurable factors are not investigated during this thesis. Especially, the strong dependencies between the lighting, the air temperature, humidity, CO_2 level and biomass production have to be investigated in future researches. The dependencies between different factors can affect the criteria weighting. The implementation of the results of a detailed analysis of the relations can improve the reliability of the proposed analysis and evaluation methodology.

The adaptability and the generality of the developed strategy allow the use in future investigation of the DLR research efforts in the niche field of greenhouse modules for space applications. The outcome can be used for future research activities in the system design of greenhouse modules, laboratories and test facilities.

6 Summary

The topic of this thesis was the system analysis and evaluation of greenhouse modules for planetary habitats. A survey on existing plant growth chambers, greenhouse modules and terrestrial test facilities had been executed to accomplish a list of concepts. For the analysis and evaluation of greenhouse modules a methodology had been developed. Therefore, measurable factors concerning the performance, agricultural properties and in-/output of greenhouse modules had been defined. The developed strategy had been executed on selected greenhouse module concepts to demonstrate the workability and reliability.

Chapter 2 of present thesis provides a profound scientific background related to environmental conditions, human requirements, ECLSS, food provision in crewed spacecraft and greenhouse module subsystems.

The first subchapter of Chapter 3 explains the developed analysis and evaluation methodology. The strategy consists of a four step approach, starting with the data acquisition, followed by the system analysis, the evaluation and the discussion. The second subchapter describes the proposed system analysis method, the Morphological Analysis, which is a suitable analysis method to structure problems. The third subchapter explains the two proposed evaluation methods, the Equivalent System Mass (ESM) approach and the Analytical Hierarchy Process (AHP). Finally, the AHP was selected, due to the advantage of using qualitative criteria. The fourth subchapter defines the investigated measurable factors. A factor categorization had been established and detailed descriptions for every factor were provided.

Chapter 4 shows an exemplary evaluation of preselected greenhouse modules. This chapter starts with a survey on existing plant growth chambers, greenhouse module concepts and terrestrial test facilities. The Lunar Greenhouse (LGH), the Lunar Food and Revitalization Module (Lunar FARM) and the Biomass Production Chamber (BPC) of the BIO-Plex facility were selected for further investigation and evaluation. The second subchapter defines the goal of the evaluation. In the third subchapter, evaluation criteria are shown and the weighting calculations of each criterion based on the AHP equations are depicted. The fourth subchapter described the results of the evaluation.

Chapter 5 discusses the outcomes of this thesis. As demonstrated the proposed analysis and evaluation strategy is suitable and reliable method for the investigation and comparison of existing greenhouse module concepts. Furthermore, the established measurable factors and evaluation criteria hierarchies can be expanded if necessary for future evaluations. In addition to the analysis and evaluation the defined factors can be used in the design phase of future greenhouse modules and can assists the designing engineer during trade studies of different systems.

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Appendix 2-1: Recommended Macronutrient Daily Dietary Intake

The following table can be found in chapter 7 of reference [**5**].

Nutrients	**Daily Dietary Intake**
Protein	0.8 g/kg
	And ≤ 35 % of the total daily energy intake
	And 2/3 of the amount in the form of animal protein and 1/3 in the form of vegetable protein
Carbohydrate	50 – 55 % of the total daily energy intake
Fat	25 – 35 % of the total daily energy intake
Ω-6 fatty acids	14 g
Ω-3 fatty acids	1.1 – 1.6 g
Saturated fat	< 7 % of the total energy intake
Trans fatty acids	< 1 % of the total energy intake
Cholesterol	< 300 mg/d
Fiber	10 – 14 g/4187 kJ

Appendix 2-2: Recommended Micronutrient Daily Dietary Intake

The following table can be found in chapter 7 of reference [**5**].

Vitamin of Mineral	Daily Dietary Intake
Vitamin A	700 – 900 µg
Vitamin D	25 µg
Vitamin K	Women: 90 µg; Men: 120 µg
Vitamin E	15 mg
Vitamin C	90 mg
Vitamin B_{12}	2.4 µg
Vitamin B_6	1.7 mg
Thiamin	Women: 1.1 µmol; Men: 1.2 µmol
Riboflavin	1.3 mg
Folate	400 µg
Niacin	16 mg niacin equivalents
Biotin	30 µg
Pantothenic acid	30 mg
Calcium	1200 – 2000 mg
Phosphorus	700 mg; and ≤ 1.5*calcium intake
Magnesium	Women: 320 mg; Men: 420 mg
Sodium	1500 – 2300 mg
Potassium	4.7 g
Iron	8 – 10 mg
Copper	0.5 – 9 mg
Manganese	Women: 1.8 mg; Men: 2.3 mg
Fluoride	Women: 3 mg; Men: 4 mg
Zinc	11 mg
Selenium	55 – 400 µg
Iodine	150 µg
Chromium	35 µg

Appendix 2-3: P/C Technologies for the Water Management

The original table can be found in reference [**10**].

Function	Technology
Distillation	Vapor Compression Distillation (VCD)
	Thermoelectric Integrated Membrane Evaporation (TIMES)
	Vapor Phase Catalytic Ammonia Removal (VAPCAR)
	Air Evaporation (AE)
Filtration	Reverse Osmosis (RO)
	Multifiltration (MF)
	Electrodialysis

Appendix 2-4: P/C Technologies for Air Revitalization

The original table can be found in reference [**10**].

Function	Technology
Carbon Dioxide Removal	2-bed Molecular Sieve (2BMS)
	4-bed Molecular Sieve (4BMS)
	Electrochemical Depolarization Concentrator (EDC)
	Solid Amine Water Desorption (SAWD)
	Air Polarized Concentrators (APC)
	Lithium Hydroxide (LiOH)
Carbon Dioxide Reduction	Bosch Process
	Sabatier Process
	Advanced Carbon-Formation Reactor System
	Carbon Dioxide Electrolysis
	Superoxides
	Artificial Gill
Oxygen Generation	Static Feed Water Electrolysis (SFWE)
	Solid Polymer Water Electrolysis (SPWE)
	Water Vapor Electrolysis (WVE)

Appendix 3-1: Morphological Box of the LGH concept

	Fundamental Factors		Environmental Factors		Agricultural Factors		Interface Factors	
	Name	Options/Unit	Name	Options/Unit	Name	Options/Unit	Name	Options/Unit
Qualitative Factors	Module Shape	Prismatic, Spherical, Hemispherical, Irregular	Lighting Type	Electrical, Hybrid, Natural	Growth Medium	Soil, Soil-like, Soilless	Water Purification	No, Partial, Full
	Arrangement of Growth Area	Shelves, Conveyor, Rotating Cylinder, Plain	Lighting Strategy	Overhead, Sidewise, Intracanopy	Nutrient Supply	Storage, Partial Recycling, Full Recycling	Air Revitalization	No, Partial, Full
	Distribution of Aisles	Center Aisle Two Shelves, Two Aisles Center Shelf, Two Aisles Three Shelves, Moveable Shelves	Atmospheric Composition	Local Planetary, Earth-like, Enriched with CO_2	Plant Monitoring	None, Per plant species, Per growth unit, Every plant	Resupply Dependency	Fresh Food, Energy Food, Quasi-Full Nutrition
	Module Structure	Rigid, Semideployable, Deployable, In-Situ	Trace Gas Treatment	None, Monitoring, Monitoring and Separation	Plant Mixture	Monoculture, Polyculture		
	Adaptability of Internal Configuration	Inflexible, Semi-flexible, Flexible	Temperature Control	Whole greenhouse, Per plant species, Per growth unit	Planting Sequence	Staggered, Combined, Batch		
	Level of Automation	None, Partial, Full						
Quantitative Factors	Specific Module Mass	[kg/m^2]	Photosynthetic Period	[µmol*h/(m^2*s)] for waveband [nm]	Biomass Productivity	[g/(m^2*d)], [g/(m^3*d)], [g/(kWh*d)]	Food Provision	≈1000 kcal/(CM*d)
	Total Module Mass	[kg]	Humidity	53.5 %	Cultivated Plants	Lettuce, Strawberry, Sweet Potato	Power Demand	[kW], [kW/m^2]
	Dimensions	L: 5.5 m; D: 2.06 m	Air Temperature	21.1 °C			Cooling Demand	[kW], [kW/m^2]
	Total Volume	21 m^3	Atmospheric Pressure	62 kPa	Specific Growth Area	8.8 m^2/CM	Water In-/Output	[kg/(m^2*d)]
	Pressurized Volume	21 m^3	CO_2 Partial Pressure	0.062 kPa	Total Growth Area	8.8 m^2	CO_2 Intake	[kg/(m^2*d)]
	Specific Cultivation Volume	0.251 m^3/m^3	O_2 Partial Pressure	21 kPa	Growth Height	up to 1 m	O_2 Output	[kg/(m^2*d)]
	Complexity						Crew Size	1
							Crew Work Load	[h/(m^2*d)]
							Psychological Health Care	Procedure

Legend: Factor with sufficient Data | Factor with insufficient Data

Appendix 3-2: Morphological Box of the Lunar FARM concept

	Fundamental Factors		Environmental Factors		Agricultural Factors		Interface Factors	
	Name	**Options/Unit**	**Name**	**Options/Unit**	**Name**	**Options/Unit**	**Name**	**Options/Unit**
Qualitative Factors	Module Shape	Prismatic, Spherical, Hemispherical, Irregular	Lighting Type	Electrical, Hybrid, Natural	Growth Medium	Soil, Soil-like, Soilless	Water Purification	No, Partial, Full
	Arrangement of Growth Area	Shelves, Conveyor, Rotating Cylinder, Plain	Lighting Strategy	Overhead, Sidewise, Intracanopy	Nutrient Supply	Storage, Partial Recycling, Full Recycling	Air Revitalization	No, Partial, Full
	Distribution of Aisles	Center Aisle Two Shelves, Two Aisles Center Shelf, Two Aisles Three Shelves, Moveable Shelves	Atmospheric Composition	Local Planetary, Earth-like, Enriched with CO_2	Plant Monitoring	None, Per plant species, Per growth unit, Every plant	Resupply Dependency	Fresh Food, Energy Food, Quasi-Full Nutrition
	Module Structure	Rigid, Semideployable, Deployable, In-Situ	Trace Gas Treatment	None, Monitoring, Monitoring and Separation	Plant Mixture	Monoculture, Polyculture		
	Adaptability of Internal Configuration	Inflexible, Semi-flexible, Flexible	Temperature Control	Whole greenhouse, Per plant species, Per growth unit	Planting Sequence	Staggered, Combined, Batch		
	Level of Automation	None, Partial, Full						
Quantitative Factors	Specific Module Mass	55.56 kg/m^2	Photosynthetic Period	[$\mu mol*h/(m^2*s)$] for waveband [nm]	Biomass Productivity	179.2 $g/(m^2*d)$	Food Provision	1753 kcal/(CM*d)
	Total Module Mass	8000 kg	Humidity	25 – 75 %	Cultivated Plants	Beans, Carrot, Green Onion, Pepper, White Potato, Straw-berry, Tomato, Wheat	Power Demand	[kW], [kW/m^2]
	Dimensions	L: 12.0 m; D: 8.0 m	Air Temperature	17 – 28 °C			Cooling Demand	[kW], [kW/m^2]
	Total Volume	603.2 m^3	Atmospheric Pressure	75.5 kPa			Water In-/Output	0.252 $kg/(m^2*d)$
	Pressurized Volume	432 m^3	CO_2 Partial Pressure	0.02 kPa			CO_2 Intake	[$kg/(m^2*d)$]
	Specific Cultivation Volume	0.128 m^3/m^3	O_2 Partial Pressure	21.1 kPa	Specific Growth Area	27 m^2/CM	O_2 Output	1.0 $kg/(m^2*d)$
	Complexity				Total Growth Area	144 m^2	Crew Size	4.5
					Growth Height	0.5 m: 96 m^2 0.3 m: 48 m^2	Crew Work Load	0.069 $h/(m^2*d)$
							Psychological Health Care	Procedure

Legend: Factor with sufficient Data (green) | Factor with insufficient Data (yellow)

Appendix 3-3: Morphological Box of the BIO-Plex concept

	Fundamental Factors		Environmental Factors		Agricultural Factors		Interface Factors	
	Name	Options/Unit	Name	Options/Unit	Name	Options/Unit	Name	Options/Unit
Qualitative Factors	Module Shape	Prismatic, Spherical, Hemispherical, Irregular	Lighting Type	Electrical, Hybrid, Natural	Growth Medium	Soil, Soil-like, Soilless	Water Purification	No, Partial, Full
	Arrangement of Growth Area	Shelves, Conveyor, Rotating Cylinder, Plain	Lighting Strategy	Overhead, Sidewise, Intracanopy	Nutrient Supply	Storage, Partial Recycling, Full Recycling	Air Revitalization	No, Partial, Full
	Distribution of Aisles	Center Aisle Two Shelves, Two Aisles Center Shelf, Two Aisles Three Shelves, Moveable Shelves	Atmospheric Composition	Local Planetary, Earth-like, Enriched with CO_2	Plant Monitoring	None, Per plant species, Per growth unit, Every plant	Resupply Dependency	Fresh Food, Energy Food, Quasi-Full Nutrition
	Module Structure	Rigid, Semideployable, Deployable, In-Situ	Trace Gas Treatment	None, Monitoring, Monitoring and Separation	Plant Mixture	Monoculture, Polyculture		
	Adaptability of Internal Configuration	Inflexible, Semi-flexible, Flexible	Temperature Control	Whole greenhouse, Per plant species, Per growth unit	Planting Sequence	Staggered, Combined, Batch		
	Level of Automation	None, Partial, Full						
Quantitative Factors	Specific Module Mass	[kg/m^2]	Photosynthetic Period	[µmol*h/(m^2*s)] for waveband [nm]	Biomass Productivity	[g/(m^2*d)], [g/(m^3*d)], [g/(kWh*d)]	Food Provision	2200 kcal/(CM*d)
	Total Module Mass	[kg]	Humidity	65 – 85 %	Cultivated Plants	e.g.: Wheat, Rice, White Potato, Soybean, Peanut, Lettuce, Chard, …	Power Demand	[kW], [kW/m^2]
	Dimensions	L: 11.3 m; D: 4.6 m	Air Temperature	16 – 35 °C			Cooling Demand	[kW], [kW/m^2]
	Total Volume	187.8 m^3	Atmospheric Pressure	101 kPa			Water In-/Output	[kg/(m^2*d)]
	Pressurized Volume	187.8 m^3	CO_2 Partial Pressure	0.03 – 1.0 kPa	Total Growth Area	82.4 m^2	CO_2 Intake	[kg/(m^2*d)]
	Specific Cultivation Volume	0.227 m^3/m^3	O_2 Partial Pressure	20 – 24 kPa	Specific Growth Area	20.6 m^2/CM	O_2 Output	[kg/(m^2*d)]
	Complexity				Growth Height	0.40 m: 6.6 m^2 0.44 m: 6.6 m^2 0.50 m: 56.8 m^2 0.70 m: 12.4 m^2	Crew Size	4
							Crew Work Load	[h/(m^2*d)]
							Psychological Health Care	Procedure

Legend: Factor with sufficient Data | Factor with insufficient Data

Appendix 4-1: Selected Evaluation Criteria

	Fundamental Factors		Environmental Factors		Agricultural Factors		Interface Factors	
	Name	Options/Unit	Name	Options/Unit	Name	Options/Unit	Name	Options/Unit
Qualitative Factors	Module Shape	Prismatic, Spherical, Hemispherical, Irregular	Lighting Type	Electrical, Hybrid, Natural	Growth Medium	Soil, Soil-like, Soilless	Water Purification	No, Partial, Full
	Arrangement of Growth Area	Shelves, Conveyor, Rotating Cylinder, Plain	Lighting Strategy	Overhead, Sidewise, Intracanopy	Nutrient Supply	Storage, Partial Recycling, Full Recycling	Air Revitalization	No, Partial, Full
	Distribution of Aisles	Center Aisle Two Shelves, Two Aisles Center Shelf, Two Aisles Three Shelves, Moveable Shelves	Atmospheric Composition	Local Planetary, Earth-like, Enriched with CO_2	Plant Monitoring	None, Per plant species, Per growth unit, Every plant	Resupply Dependency	Fresh Food, Energy Food, Quasi-Full Nutrition
	Module Structure	Rigid, Semideployable, Deployable, In-Situ	Trace Gas Treatment	None, Monitoring, Monitoring and Separation	Plant Mixture	Monoculture, Polyculture		
	Adaptability of Internal Configuration	Inflexible, Semi-flexible, Flexible	Temperature Control	Whole greenhouse, Per plant species, Per growth unit	Planting Sequence	Staggered, Combined, Batch		
	Level of Automation	None, Partial, Full						
Quantitative Factors	Specific Module Mass	[kg/m^2]	Photosynthetic Period	[µmol*h/(m^2*s)] for waveband [nm]	Biomass Productivity	[g/(m^2*d)], [g/(m^3*d)], [g/(kWh*d)]	Food Provision	[kcal/(CM*d)], [g/(CM*d)]
	Total Module Mass	[kg]	Humidity	[g/cm^3], [%]	Cultivated Plants	Species: [m^2]	Power Demand	[kW], [kW/m^2]
	Dimensions	[m]	Air Temperature	[°C]	Total Growth Area	[m^2]	Cooling Demand	[kW], [kW/m^2]
	Total Volume	[m^3]	Atmospheric Pressure	[kPa]	Specific Growth Area	[m^2/CM]	Water In-/Output	[kg/(m^2*d)]
	Pressurized Volume	[m^3]	CO_2 Partial Pressure	[kPa]	Growth Height	[m], [m/m^2]	CO_2 Intake	[kg/(m^2*d)]
	Specific Cultivation Volume	[m^3/m^3]	O_2 Partial Pressure	[kPa]			O_2 Output	[kg/(m^2*d)]
	Complexity						Crew Size	Number
							Crew Work Load	[h/(m^2*d)]
							Psychological Health Care	Procedure

Legend: Selected Evaluation Criteria | Criteria with insufficient Data | Parameters

Appendix 4-2: Calculation of Hierarchy Level 1

FC: Fundamental Criteria **EC:** Environmental Criteria **AC:** Agricultural Criteria **IC:** Interface Criteria

	Comparison Matrix				Normalization					Weighting
	FC	**EC**	**AC**	**IC**	**FC**	**EC**	**AC**	**IC**	**Σ Row**	**w**
FC	1	0.250	0.333	3.000	0.120	0.134	0.094	0.167	0.515	**0.129**
EC	4.000	1	2.000	9.000	0.480	0.537	0.566	0.500	2.083	**0.521**
AC	3.000	0.500	1	5.000	0.360	0.269	0.283	0.278	1.189	**0.297**
IC	0.333	0.111	0.200	1	0.040	0.060	0.057	0.056	0.212	**0.053**
Σ Column	8.333	1.861	3.533	18.000	1.000	1.000	1.000	1.000	4.000	**1.000**

	Mean Matrix					
	FC	**EC**	**AC**	**IC**	**Σ Row**	**λ**
FC	0.129	0.130	0.099	0.159	0.517	4.013
EC	0.515	0.521	0.595	0.477	2.108	4.047
AC	0.387	0.260	0.297	0.265	1.209	4.066
IC	0.043	0.058	0.059	0.053	0.213	4.026

n =	4
λ_max =	4.038
CI =	1.27E-02

n	1	2	3	4	5	6	7	8	9	10
R	0.00	0.00	0.52	0.89	1.11	1.23	1.35	1.40	1.45	1.49

CR =	0.014	**Boundary Value =**	0.1

Evaluation consistent?	Yes

Appendix 4-3: Calculation of Hierarchy Level 2-FC

LA: Level of Automation
AIC: Adaptability of Internal Configuration
SCV: Specific Cultivation Volume
AGA: Arrangement of Growth Area
MS: Module Structure

	Comparison Matrix					Normalization						Weighting
	LA	AIC	SCV	MS	AGA	LA	AIC	SCV	MS	AGA	Σ Row	w
LA	1	3.000	0.200	0.333	0.500	0.088	0.214	0.088	0.085	0.057	0.532	**0.106**
AIC	0.333	1	0.333	0.250	0.333	0.029	0.071	0.146	0.064	0.038	0.348	**0.070**
SCV	5.000	3.000	1	2.000	4.000	0.441	0.214	0.438	0.511	0.453	2.057	**0.411**
MS	3.000	4.000	0.500	1	3.000	0.265	0.286	0.219	0.255	0.340	1.364	**0.273**
AGA	2.000	3.000	0.250	0.333	1	0.176	0.214	0.109	0.085	0.113	0.699	**0.140**
Σ Column	11.333	14.000	2.283	3.917	8.833	1.000	1.000	1.000	1.000	1.000	5.000	**1.000**

	Mean Matrix						
	LA	AIC	SCV	MS	AGA	Σ Row	λ
LA	0.106	0.209	0.082	0.091	0.070	0.558	5.251
AIC	0.035	0.070	0.137	0.068	0.047	0.357	5.124
SCV	0.532	0.209	0.411	0.546	0.559	2.257	5.486
MS	0.319	0.279	0.206	0.273	0.419	1.495	5.481
AGA	0.213	0.209	0.103	0.091	0.140	0.755	5.406

n =	5
λ_max =	5.350
CI =	8.74E-02

n	1	2	3	4	5	6	7	8	9	10
R	0.00	0.00	0.52	0.89	1.11	1.23	1.35	1.40	1.45	1.49

CR =	0.079	**Boundary Value =**	0.1

Evaluation consistent?	Yes

Appendix 4-4: Calculation of Hierarchy Level 3-FC-LA

Level of Automation

	Comparison Matrix			Normalization				Weighting
	None	Partial	Full	None	Partial	Full	Σ Row	w
None	1	0.333	0.111	0.077	0.045	0.087	0.209	**0.070**
Partial	3.000	1	0.167	0.231	0.136	0.130	0.498	**0.166**
Full	9.000	6.000	1	0.692	0.818	0.783	2.293	**0.764**
Σ Column	13.000	7.333	1.278	1.000	1.000	1.000	3.000	**1.000**

	Mean Matrix				
	None	Partial	Full	Σ Row	λ
None	0.070	0.055	0.085	0.210	3.009
Partial	0.209	0.166	0.127	0.503	3.030
Full	0.628	0.995	0.764	2.388	3.124

n =	3
λ_max =	3.054
CI =	2.72E-02

n	1	2	3	4	5	6	7	8	9	10
R	0.00	0.00	0.52	0.89	1.11	1.23	1.35	1.40	1.45	1.49

CR =	0.052	**Boundary Value =**	0.1

Evaluation consistent?	Yes

Appendix 4-5: Calculation of Hierarchy Level 3-FC-AIC

Adaptability of Internal Configuration

	Comparison Matrix			Normalization				Weighting
	Inflexible	Semiflexible	Flexible	Inflexible	Semiflexible	Flexible	Σ Row	w
Inflexible	1	0.250	0.143	0.083	0.048	0.103	0.234	**0.078**
Semiflexible	4.000	1	0.250	0.333	0.190	0.179	0.703	**0.234**
Flexible	7.000	4.000	1	0.583	0.762	0.718	2.063	**0.688**
Σ Column	12.000	5.250	1.393	1.000	1.000	1.000	3.000	**1.000**

	Mean Matrix				
	Inflexible	Semiflexible	Flexible	Σ Row	λ
Inflexible	0.078	0.059	0.098	0.235	3.015
Semiflexible	0.311	0.234	0.172	0.718	3.062
Flexible	0.545	0.938	0.688	2.170	3.156

n =	3
λ_max =	3.077
CI =	3.87E-02

n	1	2	3	4	5	6	7	8	9	10
R	0.00	0.00	0.52	0.89	1.11	1.23	1.35	1.40	1.45	1.49

CR =	0.075
Boundary Value =	0.1
Evaluation consistent?	Yes

Appendix 4-6: Calculation of Hierarchy Level 3-FC-SCV

	LGH	Lunar FARM	BIO-Plex
Specific Cultivation Volume	0.25121	0.12824	0.22696

Weighting	0.414	0.211	0.374

Appendix 4-7: Calculation of Hierarchy Level 3-FC-MS

Module Structure

	Comparison Matrix				Normalization					Weighting
	Rigid	Semi-deployable	Deployable	In-Situ	Rigid	Semi-deployable	Deployable	In-Situ	Σ Row	w
Rigid	1	0.250	0.500	0.167	0.077	0.067	0.077	0.083	0.304	**0.076**
Semideployable	4.000	1	2.000	0.500	0.308	0.267	0.308	0.250	1.132	**0.283**
Deployable	2.000	0.500	1	0.333	0.154	0.133	0.154	0.167	0.608	**0.152**
In-Situ	6.000	2.000	3.000	1	0.462	0.533	0.462	0.500	1.956	**0.489**
Σ Column	13.000	3.750	6.500	2.000	1.000	1.000	1.000	1.000	4.000	**1.000**

	Mean Matrix					
	Rigid	Semi-deployable	Deployable	In-Situ	Σ Row	λ
Rigid	0.076	0.071	0.076	0.082	0.304	4.005
Semideployable	0.304	0.283	0.304	0.245	1.135	4.011
Deployable	0.152	0.142	0.152	0.163	0.608	4.005
In-Situ	0.456	0.566	0.456	0.489	1.967	4.021

n =	4
λ_max =	4.010
CI =	3.45E-03

n	1	2	3	4	5	6	7	8	9	10
R	0.00	0.00	0.52	0.89	1.11	1.23	1.35	1.40	1.45	1.49

CR =	0.004
Boundary Value =	0.1

Evaluation consistent?	Yes

Appendix 4-8: Calculation of Hierarchy Level 3-FC-AGA

Arrangement of Growth Area

	Comparison Matrix				Normalization					Weighting
	Shelves	Conveyor	Rotating Cylinder	Plain	Shelves	Conveyor	Rotating Cylinder	Plain	Σ Row	w
Shelves	1	3.000	5.000	9.000	0.608	0.646	0.600	0.450	2.304	**0.576**
Conveyor	0.333	1	2.000	7.000	0.203	0.215	0.240	0.350	1.008	**0.252**
Rotating Cylinder	0.200	0.500	1	3.000	0.122	0.108	0.120	0.150	0.499	**0.125**
Plain	0.111	0.143	0.333	1	0.068	0.031	0.040	0.050	0.188	**0.047**
Σ Column	1.644	4.643	8.333	20.000	1.000	1.000	1.000	1.000	4.000	**1.000**

	Mean Matrix					
	Shelves	Conveyor	Rotating Cylinder	Plain	Σ Row	λ
Shelves	0.576	0.756	0.624	0.424	2.380	4.132
Conveyor	0.192	0.252	0.250	0.330	1.023	4.060
Rotating Cylinder	0.115	0.126	0.125	0.141	0.507	4.064
Plain	0.064	0.036	0.042	0.047	0.189	4.008

n =	4
λ_max =	4.066
CI =	2.20E-02

n	1	2	3	4	5	6	7	8	9	10
R	0.00	0.00	0.52	0.89	1.11	1.23	1.35	1.40	1.45	1.49

CR =	0.025	**Boundary Value =**	0.1

Evaluation consistent?	Yes

Appendix 4-9: Calculation of Hierarchy Level 2-EC

LT: Lighting Type **LS:** Lighting Strategy **AtC:** Atmospheric Composition **TC:** Temperature Control

	Comparison Matrix				Normalization					Weighting
	LT	LS	AtC	TC	LT	LS	AtC	TC	Σ Row	w
LT	1	3.000	2.000	5.000	0.492	0.409	0.522	0.455	1.877	**0.469**
LS	0.333	1	0.333	3.000	0.164	0.136	0.087	0.273	0.660	**0.165**
AtC	0.500	3.000	1	2.000	0.246	0.409	0.261	0.182	1.098	**0.274**
TC	0.200	0.333	0.500	1	0.098	0.045	0.130	0.091	0.365	**0.091**
Σ Column	2.033	7.333	3.833	11.000	1.000	1.000	1.000	1.000	4.000	**1.000**

	Mean Matrix					
	LT	LS	AtC	TC	Σ Row	λ
LT	0.469	0.495	0.549	0.456	1.970	4.197
LS	0.156	0.165	0.091	0.274	0.687	4.162
AtC	0.235	0.495	0.274	0.183	1.187	4.324
TC	0.094	0.055	0.137	0.091	0.377	4.134

n =	4
λ_max =	4.204
CI =	6.81E-02

n	1	2	3	4	5	6	7	8	9	10
R	0.00	0.00	0.52	0.89	1.11	1.23	1.35	1.40	1.45	1.49

CR =	0.076

Boundary Value =	0.1

Evaluation consistent?	Yes

Appendix 4-10: Calculation of Hierarchy Level 3-EC-LT

Lighting Type

	Comparison Matrix			Normalization				Weighting
	Electrical	Hybrid	Natural	Electrical	Hybrid	Natural	Σ Row	w
Electrical	1	3.000	1.000	0.429	0.429	0.429	1.286	**0.429**
Hybrid	0.333	1	0.333	0.143	0.143	0.143	0.429	**0.143**
Natural	1.000	3.000	1	0.429	0.429	0.429	1.286	**0.429**
Σ Column	2.333	7.000	2.333	1.000	1.000	1.000	3.000	**1.000**

	Mean Matrix				
	Electrical	Hybrid	Natural	Σ Row	λ
Electrical	0.429	0.429	0.429	1.286	3.000
Hybrid	0.143	0.143	0.143	0.429	3.000
Natural	0.429	0.429	0.429	1.286	3.000

n =	3
λ_max =	3.000
CI =	0.00E+00

n	1	2	3	4	5	6	7	8	9	10
R	0.00	0.00	0.52	0.89	1.11	1.23	1.35	1.40	1.45	1.49

CR =	0.000	**Boundary Value =**	0.1

Evaluation consistent?	Yes

Appendix 4-11: Calculation of Hierarchy Level 4-EC-LT-EL

HPS: High Pressure Sodium **MH:** Metal Halide **LED:** Light Emitting Diode

	Comparison Matrix					Normalization						Weighting
	HPS	MH	Fluorescent	Sulfur Lamps	LED	HPS	MH	Fluorescent	Sulfur Lamps	LED	Σ Row	w
HPS	1	2.000	1.000	0.333	0.125	0.074	0.100	0.074	0.069	0.074	0.391	**0.078**
MH	0.500	1	0.500	0.167	0.111	0.037	0.050	0.037	0.034	0.066	0.224	**0.045**
Fluorescent	1.000	2.000	1	0.333	0.125	0.074	0.100	0.074	0.069	0.074	0.391	**0.078**
Sulfur Lamps	3.000	6.000	3.000	1	0.333	0.222	0.300	0.222	0.207	0.197	1.148	**0.230**
LED	8.000	9.000	8.000	3.000	1	0.593	0.450	0.593	0.621	0.590	2.846	**0.569**
Σ Column	13.500	20.000	13.500	4.833	1.694	1.000	1.000	1.000	1.000	1.000	5.000	**1.000**

	Mean Matrix						
	HPS	MH	Fluorescent	Sulfur Lamps	LED	Σ Row	λ
HPS	0.078	0.090	0.078	0.077	0.071	0.394	5.036
MH	0.039	0.045	0.039	0.038	0.063	0.225	5.009
Fluorescent	0.078	0.090	0.078	0.077	0.071	0.394	5.036
Sulfur Lamps	0.235	0.269	0.235	0.230	0.190	1.157	5.041
LED	0.625	0.403	0.625	0.689	0.569	2.912	5.116

n =	5
λ_max =	5.047
CI =	1.19E-02

n	1	2	3	4	5	6	7	8	9	10
R	0.00	0.00	0.52	0.89	1.11	1.23	1.35	1.40	1.45	1.49

CR =	0.011	**Boundary Value =**	0.1

Evaluation consistent?	Yes

Appendix 4-12: Calculation of Hierarchy Level 4-EC-LT-NL

Natural Lighting

	Comparison Matrix		Normalization			Weighting
	Direct	Indirect	Direct	Indirect	Σ Row	w
Direct	1	0.143	0.125	0.125	0.250	**0.125**
Indirect	7.000	1	0.875	0.875	1.750	**0.875**
Σ Column	8.000	1.143	1.000	1.000	2.000	**1.000**

	Mean Matrix			
	Direct	Indirect	Σ Row	λ
Direct	0.125	0.125	0.250	2.000
Indirect	0.875	0.875	1.750	2.000

n =	2
λ_max =	2.000
CI =	0.00E+00

n	1	2	3	4	5	6	7	8	9	10
R	0.00	0.00	0.52	0.89	1.11	1.23	1.35	1.40	1.45	1.49

CR =	0.000	**Boundary Value =**	0.1

Evaluation consistent?	Yes

Appendix 4-13: Calculation of Hierarchy Level 3-EC-LS

Lighting Strategy

	Comparison Matrix			Normalization				Weighting
	Overhead	Sidewise	Intracanopy	Overhead	Sidewise	Intracanopy	Σ Row	w
Overhead	1	5.000	0.333	0.238	0.333	0.231	0.802	**0.267**
Sidewise	0.200	1	0.111	0.048	0.067	0.077	0.191	**0.064**
Intracanopy	3.000	9.000	1	0.714	0.600	0.692	2.007	**0.669**
Σ Column	4.200	15.000	1.444	1.000	1.000	1.000	3.000	**1.000**

	Mean Matrix				
	Overhead	Sidewise	Intracanopy	Σ Row	λ
Overhead	0.267	0.319	0.223	0.809	3.026
Sidewise	0.053	0.064	0.074	0.192	3.005
Intracanopy	0.802	0.574	0.669	2.045	3.057

n =	3
λ_max =	3.029
CI =	1.46E-02

n	1	2	3	4	5	6	7	8	9	10
R	0.00	0.00	0.52	0.89	1.11	1.23	1.35	1.40	1.45	1.49

CR =	0.028	**Boundary Value =**	0.1

Evaluation consistent?	Yes

Appendix 4-14: Calculation of Hierarchy Level 3-EC-AtC

Atmopsheric Composition

	Comparison Matrix			Normalization				Weighting
	Local Plane-tary	Earth-Like	Enriched with CO_2	Local Plane-tary	Earth-Like	Enriched with CO_2	Σ Row	w
Local Planetary	1	1.000	0.111	0.091	0.091	0.091	0.273	**0.091**
Earth-Like	1.000	1	0.111	0.091	0.091	0.091	0.273	**0.091**
Enriched with CO_2	9.000	9.000	1	0.818	0.818	0.818	2.455	**0.818**
Σ Column	11.000	11.000	1.222	1.000	1.000	1.000	3.000	**1.000**

	Mean Matrix				
	Local Plane-tary	Earth-Like	Enriched with CO_2	Σ Row	λ
Local Planetary	0.091	0.091	0.091	0.273	3.000
Earth-Like	0.091	0.091	0.091	0.273	3.000
Enriched with CO_2	0.818	0.818	0.818	2.455	3.000

n =	3
λ_max =	3.000
CI =	0.00E+00

n	1	2	3	4	5	6	7	8	9	10
R	0.00	0.00	0.52	0.89	1.11	1.23	1.35	1.40	1.45	1.49

CR =	0.000	**Boundary Value =**	0.1

Evaluation consistent?	Yes

Appendix 4-15: Calculation of Hierarchy Level 3-EC-TC

Temperature Control

	Comparison Matrix			Normalization				Weighting
	Whole Greenhouse	Per Plant Species	Per Growth Unit	Whole Greenhouse	Per Plant Species	Per Growth Unit	Σ Row	w
Whole Greenhouse	1	0.333	0.125	0.083	0.077	0.086	0.246	**0.082**
Per Plant Species	3.000	1	0.333	0.250	0.231	0.229	0.709	**0.236**
Per Growth Unit	8.000	3.000	1	0.667	0.692	0.686	2.045	**0.682**
Σ Column	12.000	4.333	1.458	1.000	1.000	1.000	3.000	**1.000**

	Mean Matrix				
	Whole Greenhouse	Per Plant Species	Per Growth Unit	Σ Row	λ
Whole Greenhouse	0.082	0.079	0.085	0.246	3.000
Per Plant Species	0.246	0.236	0.227	0.710	3.001
Per Growth Unit	0.656	0.709	0.682	2.047	3.003

n =	3
λ_max =	3.002
CI =	7.71E-04

n	1	2	3	4	5	6	7	8	9	10
R	0.00	0.00	0.52	0.89	1.11	1.23	1.35	1.40	1.45	1.49

CR =	0.001	Boundary Value =	0.1

Evaluation consistent?	Yes

Appendix 4-16: Calculation of Hierarchy Level 2-AC

GM: Growth Medium **PM:** Plant Mixture **PS:** Planting Sequence **SGA:** Specific Growth Area

	Comparison Matrix			Normalization				Weighting
	GM	PM	PS	GM	PM	PS	Σ Row	w
GM	1	3.000	4.000	0.632	0.667	0.571	1.870	**0.623**
PM	0.333	1	2.000	0.211	0.222	0.286	0.718	**0.239**
PS	0.250	0.500	1	0.158	0.111	0.143	0.412	**0.137**
Σ Column	1.583	4.500	7.000	1.000	1.000	1.000	3.000	**1.000**

	Mean Matrix				
	GM	PM	PS	Σ Row	λ
GM	0.623	0.718	0.549	1.891	3.034
PM	0.208	0.239	0.275	0.722	3.014
PS	0.156	0.120	0.137	0.413	3.007

n =	3
λ_max =	3.018
CI =	9.17E-03

n	1	2	3	4	5	6	7	8	9	10
R	0.00	0.00	0.52	0.89	1.11	1.23	1.35	1.40	1.45	1.49

CR =	0.018	**Boundary Value =**	0.1

Evaluation consistent?	Yes

Appendix 4-17: Calculation of Hierarchy Level 3-AC-GM

Growth Medium

	Comparison Matrix			Normalization				Weighting
	Soil	**Soil-Like**	**Soilless**	**Soil**	**Soil-Like**	**Soilless**	**Σ Row**	**w**
Soil	1	0.333	0.125	0.083	0.077	0.086	0.246	**0.082**
Soil-Like	3.000	1	0.333	0.250	0.231	0.229	0.709	**0.236**
Soilless	8.000	3.000	1	0.667	0.692	0.686	2.045	**0.682**
Σ Column	12.000	4.333	1.458	1.000	1.000	1.000	3.000	**1.000**

	Mean Matrix				
	Soil	**Soil-Like**	**Soilless**	**Σ Row**	**λ**
Soil	0.082	0.079	0.085	0.246	3.000
Soil-Like	0.246	0.236	0.227	0.710	3.001
Soilless	0.656	0.709	0.682	2.047	3.003

n =	3
λ_max =	3.002
CI =	7.71E-04

n	1	2	3	4	5	6	7	8	9	10
R	0.00	0.00	0.52	0.89	1.11	1.23	1.35	1.40	1.45	1.49

CR =	0.001	**Boundary Value =**	0.1

Evaluation consistent?	Yes

Appendix 4-18: Calculation of Hierarchy Level 4-AC-GM-S

Soil

	Comparison Matrix		Normalization			Weighting
	Terrestrial	Extraterres-trial	Terrestrial	Extraterres-trial	Σ Row	w
Terrestrial	1	0.250	0.200	0.200	0.400	**0.200**
Extraterrestrial	4.000	1	0.800	0.800	1.600	**0.800**
Σ Column	5.000	1.250	1.000	1.000	2.000	**1.000**

	Mean Matrix			
	Terrestrial	Extraterres-trial	Σ Row	λ
Terrestrial	0.200	0.200	0.400	2.000
Extraterrestrial	0.800	0.800	1.600	2.000

XL

n =	2
λ_max =	2.000
CI =	0.00E+00

n	1	2	3	4	5	6	7	8	9	10
R	0.00	0.00	0.52	0.89	1.11	1.23	1.35	1.40	1.45	1.49

CR =	0.000	**Boundary Value =**	0.1

Evaluation consistent?	Yes

Appendix 4-19: Calculation of Hierarchy Level 4-AC-GM-SL

Soil-Like

	Comparison Matrix		Normalization			Weighting
	Organic	Inert	Organic	Inert	Σ Row	w
Organic	1	0.200	0.167	0.167	0.333	**0.167**
Inert	5.000	1	0.833	0.833	1.667	**0.833**
Σ Column	6.000	1.200	1.000	1.000	2.000	**1.000**

	Mean Matrix			
	Organic	Inert	Σ Row	λ
Organic	0.167	0.167	0.333	2.000
Inert	0.833	0.833	1.667	2.000

n =	2
λ_max =	2.000
CI =	0.00E+00

n	1	2	3	4	5	6	7	8	9	10
R	0.00	0.00	0.52	0.89	1.11	1.23	1.35	1.40	1.45	1.49

CR =	0.000	**Boundary Value =**	0.1

Evaluation consistent?	Yes

Appendix 4-20: Calculation of Hierarchy Level 4-AC-GM-SS

Soilless

	Comparison Matrix		Normalization			Weighting
	Hydroponic	**Aeroponic**	**Hydroponic**	**Aeroponic**	**Σ Row**	**w**
Hydroponic	1	6.000	0.857	0.857	1.714	**0.857**
Aeroponic	0.167	1	0.143	0.143	0.286	**0.143**
Σ Column	1.167	7.000	1.000	1.000	2.000	**1.000**

	Mean Matrix			
	Hydroponic	**Aeroponic**	**Σ Row**	**λ**
Hydroponic	0.857	0.857	1.714	2.000
Aeroponic	0.143	0.143	0.286	2.000

n =	2
λ_max =	2.000
CI =	0.00E+00

n	1	2	3	4	5	6	7	8	9	10
R	0.00	0.00	0.52	0.89	1.11	1.23	1.35	1.40	1.45	1.49

CR =	0.000	**Boundary Value =**	0.1

Evaluation consistent?	Yes

Appendix 4-21: Calculation of Hierarchy Level 3-AC-PM

Plant Mixture

	Comparison Matrix		Normalization			Weighting
	Monoculture	Polyculture	Monoculture	Polyculture	Σ Row	w
Monoculture	1	5.000	0.833	0.833	1.667	**0.833**
Polyculture	0.200	1	0.167	0.167	0.333	**0.167**
Σ Column	1.200	6.000	1.000	1.000	2.000	**1.000**

	Mean Matrix			
	Monoculture	Polyculture	Σ Row	λ
Monoculture	0.833	0.833	1.667	2.000
Polyculture	0.167	0.167	0.333	2.000

n =	2
λ_max =	2.000
CI =	0.00E+00

n	1	2	3	4	5	6	7	8	9	10
R	0.00	0.00	0.52	0.89	1.11	1.23	1.35	1.40	1.45	1.49

CR =	0.000	**Boundary Value =**	0.1

Evaluation consistent?	Yes

Appendix 4-22: Calculation of Hierarchy Level 3-AC-PS

Planting Sequence

	Comparison Matrix			Normalization				Weighting
	Staggered	**Combined**	**Batch**	**Staggered**	**Combined**	**Batch**	**Σ Row**	**w**
Staggered	1	0.200	1.000	0.143	0.143	0.143	0.429	**0.143**
Combined	5.000	1	5.000	0.714	0.714	0.714	2.143	**0.714**
Batch	1.000	0.200	1	0.143	0.143	0.143	0.429	**0.143**
Σ Column	7.000	1.400	7.000	1.000	1.000	1.000	3.000	**1.000**

	Mean Matrix				
	Staggered	**Combined**	**Batch**	**Σ Row**	**λ**
Staggered	0.143	0.143	0.143	0.429	3.000
Combined	0.714	0.714	0.714	2.143	3.000
Batch	0.143	0.143	0.143	0.429	3.000

n =	3
λ_max =	3.000
CI =	0.00E+00

n	1	2	3	4	5	6	7	8	9	10
R	0.00	0.00	0.52	0.89	1.11	1.23	1.35	1.40	1.45	1.49

CR =	0.000	**Boundary Value =**	0.1

Evaluation consistent?	Yes

Appendix 4-23: Calculation of Hierarchy Level 2-IC

WP: Water Purification **AR:** Air Revitalization **RD:** Resupply Dependency **FP:** Food Provision

	Comparison Matrix				Normalization					Weighting
	WP	AR	RD	FP	WP	AR	RD	FP	Σ Row	w
WP	1	1.000	0.200	0.111	0.063	0.063	0.059	0.065	0.248	**0.062**
AR	1.000	1	0.200	0.111	0.063	0.063	0.059	0.065	0.248	**0.062**
RD	5.000	5.000	1	0.500	0.313	0.313	0.294	0.290	1.209	**0.302**
FP	9.000	9.000	2.000	1	0.563	0.563	0.588	0.581	2.294	**0.573**
Σ Column	16.000	16.000	3.400	1.722	1.000	1.000	1.000	1.000	4.000	**1.000**

	Mean Matrix					
	WP	AR	RD	FP	Σ Row	λ
WP	0.062	0.062	0.060	0.064	0.248	4.000
AR	0.062	0.062	0.060	0.064	0.248	4.000
RD	0.310	0.310	0.302	0.287	1.210	4.002
FP	0.559	0.559	0.605	0.573	2.296	4.003

n =	4
λ_max =	4.001
CI =	4.63E-04

n	1	2	3	4	5	6	7	8	9	10
R	0.00	0.00	0.52	0.89	1.11	1.23	1.35	1.40	1.45	1.49

CR =	0.001	**Boundary Value =**	0.1

Evaluation consistent?	Yes

Appendix 4-24: Calculation of Hierarchy Level 3-IC-WP

Water Purification

	Comparison Matrix			Normalization				Weighting
	No	**Partial**	**Full**	**No**	**Partial**	**Full**	**Σ Row**	**w**
No	1	0.250	0.111	0.071	0.077	0.069	0.217	**0.072**
Partial	4.000	1	0.500	0.286	0.308	0.310	0.904	**0.301**
Full	9.000	2.000	1	0.643	0.615	0.621	1.879	**0.626**
Σ Column	14.000	3.250	1.611	1.000	1.000	1.000	3.000	**1.000**

	Mean Matrix				
	No	**Partial**	**Full**	**Σ Row**	**λ**
No	0.072	0.075	0.070	0.217	3.000
Partial	0.290	0.301	0.313	0.904	3.001
Full	0.652	0.603	0.626	1.881	3.003

n =	3
λ_max =	3.002
CI =	7.71E-04

n	1	2	3	4	5	6	7	8	9	10
R	0.00	0.00	0.52	0.89	1.11	1.23	1.35	1.40	1.45	1.49

CR =	0.001	**Boundary Value =**	0.1

Evaluation consistent?	Yes

Appendix 4-25: Calculation of Hierarchy Level 3-IC-AR

Air Revitalization

	Comparison Matrix			Normalization				Weighting
	No	**Partial**	**Full**	**No**	**Partial**	**Full**	**Σ Row**	**w**
No	1	0.250	0.111	0.071	0.077	0.069	0.217	**0.072**
Partial	4.000	1	0.500	0.286	0.308	0.310	0.904	**0.301**
Full	9.000	2.000	1	0.643	0.615	0.621	1.879	**0.626**
Σ Column	14.000	3.250	1.611	1.000	1.000	1.000	3.000	**1.000**

	Mean Matrix				
	No	**Partial**	**Full**	**Σ Row**	**λ**
No	0.072	0.075	0.070	0.217	3.000
Partial	0.290	0.301	0.313	0.904	3.001
Full	0.652	0.603	0.626	1.881	3.003

n =	3
λ_max =	3.002
CI =	7.71E-04

n	1	2	3	4	5	6	7	8	9	10
R	0.00	0.00	0.52	0.89	1.11	1.23	1.35	1.40	1.45	1.49

CR =	0.001	**Boundary Value =**	0.1

Evaluation consistent?	Yes

Appendix 4-26: Calculation of Hierarchy Level 3-IC-RD

Resupply Dependency

	Comparison Matrix			Normalization				Weighting
	Fresh Food	Energy Food	Quasi-Full Nutrition	Fresh Food	Energy Food	Quasi-Full Nutrition	Σ Row	w
Fresh Food	1	0.200	0.111	0.067	0.048	0.077	0.191	**0.064**
Energy Food	5.000	1	0.333	0.333	0.238	0.231	0.802	**0.267**
Quasi-Full Nutrition	9.000	3.000	1	0.600	0.714	0.692	2.007	**0.669**
Σ Column	15.000	4.200	1.444	1.000	1.000	1.000	3.000	**1.000**

	Mean Matrix				
	Fresh Food	Energy Food	Quasi-Full Nutrition	Σ Row	λ
Fresh Food	0.064	0.053	0.074	0.192	3.005
Energy Food	0.319	0.267	0.223	0.809	3.026
Quasi-Full Nutrition	0.574	0.802	0.669	2.045	3.057

n =	3
λ_max =	3.029
CI =	1.46E-02

n	1	2	3	4	5	6	7	8	9	10
R	0.00	0.00	0.52	0.89	1.11	1.23	1.35	1.40	1.45	1.49

CR =	0.028	**Boundary Value =**	0.1

Evaluation consistent?	Yes

Appendix 4-27: Calculation of Hierarchy Level 3-IC-FP

Food Provision

	LGH	Lunar FARM	BIO-Plex
Food Provision [kcal/(CM*d)]	1000	1753	2200
Optimum = 2300 kcal/(CM*d)			
Difference to Optimum	1300	547	100
Weighting	0.061062737	0.145121679	0.793815584

Appendix 4-28: Local and Global Weighting Factors for each Level of the Hierarchy

Fundamental Criteria

Level 1	Local Value	Level 2	Local Value	Level 3	Local Value	Level 4	Local Value	Global Value
FC	0,12883	LA	0,10636	None	0,06978			**0,00096**
				Partial	0,16586			**0,00227**
				Full	0,76437			**0,01047**
		AIC	0,06968	Inflexible	0,07784			**0,00070**
				Semi-flexible	0,23443			**0,00210**
				Flexible	0,68773			**0,00617**
		SCV	0,41138	LGH	0,41426			**0,02196**
				Lunar FARM	0,21148			**0,01121**
				BIO-Plex	0,37427			**0,01984**
		MS	0,27287	Rigid	0,07596			**0,00267**
				Semi-deployable	0,28301			**0,00995**
				Deployable	0,15192			**0,00534**
				In-Situ	0,48910			**0,01719**
		AGA	0,13971	Shelves	0,57607			**0,01037**
				Conveyor	0,25202			**0,00454**
				Rotating Cylinder	0,12483			**0,00225**
				Plain	0,04708			**0,00085**

Environmental Criteria

Level 1	Local Value	Level 2	Local Value	Level 3	Local Value	Level 4	Local Value	Global Value
EC	0,52084	LT	0,46929	Electrical	0,42857	HPS	0,07818	**0,00819**
						MH	0,04483	**0,00470**
						Fluorescent	0,07818	**0,00819**
						Sulfur Lamp	0,22961	**0,02405**
						LED	0,56921	**0,05963**
				Hybrid	0,14286			**0,03492**
				Natural	0,42857	Direct	0,12500	**0,01309**
						Indirect	0,87500	**0,09166**
		LS	0,16500	Overhead	0,26740			**0,02298**
				Sidewise	0,06374			**0,00548**
				Intracanopy	0,66886			**0,05748**
		AtC	0,27442	Local Planetary	0,09091			**0,01299**
				Earth-Like	0,09091			**0,01299**
				Enriched with CO2	0,81818			**0,11694**
		TC	0,09129	Whole Greenhouse	0,08199			**0,00390**
				Per Plant Species	0,23645			**0,01124**
				Per Growth Unit	0,68156			**0,03241**

Agricultural Criteria

Level 1	Local Value	Level 2	Local Value	Level 3	Local Value	Level 4	Local Value	Global Value
AC	0,29736	GM	0,62322	Soil	0,08199	Terrestrial	0,20000	**0,00304**
						Extraterrestrial	0,80000	**0,01216**
				Soil-Like	0,23645	Organic	0,16667	**0,00730**
						Inert	0,83333	**0,03652**
				Soilless	0,68156	Hydroponic	0,85714	**0,10827**
						Aeroponic	0,14286	**0,01804**
		PM	0,23949	Monoculture	0,83333			**0,05935**
				Polyculture	0,16667			**0,01187**
		PS	0,13729	Staggered	0,14286			**0,00583**
				Combined	0,71429			**0,02916**
				Batch	0,14286			**0,00583**

Interface Criteria

Level 1	Local Value	Level 2	Local Value	Level 3	Local Value	Level 4	Local Value	Global Value
IC	0,05297	WP	0,06208	No	0,07244			**0,00024**
				Partial	0,30125			**0,00099**
				Full	0,62631			**0,00206**
		AR	0,06208	No	0,07244			**0,00024**
				Partial	0,30125			**0,00099**
				Full	0,62631			**0,00206**
		RD	0,30236	Fresh Food	0,06374			**0,00102**
				Energy Food	0,26740			**0,00428**
				Quasi-Full Nutrition	0,66886			**0,01071**
		FP	0,57347	LGH	0,06106			**0,00185**
				Lunar FARM	0,14512			**0,00441**
				BIO-Plex	0,79382			**0,02411**

Appendix 4-29: Global Weighting Scores for the LGH Concept

LGH			Total Score	0.31608
Level 1	**Level 2**	**Level 3**	**Level 4**	**Global Weighting**
FC	LA	Partial		0.00227
	AIC	Inflexible		0.00070
	SCV			0.02196
	MS	Deployable		0.00534
	AGA	Plain		0.00085
Level 1	**Level 2**	**Level 3**	**Level 4**	**Global Weighting**
EC	LT	Electrical	HPS	0.00819
	LS	Overhead		0.02298
	AtC	Enriched with CO2		0.11694
	TC	Whole Greenhouse		0.00390
Level 1	**Level 2**	**Level 3**	**Level 4**	**Global Weighting**
AC	GM	Soilless	Hydroponic	0.10827
	PM	Polyculture		0.01187
	PS	Staggered		0.00583
Level 1	**Level 2**	**Level 3**	**Level 4**	**Global Weighting**
IC	WP	Full		0.00206
	AR	Full		0.00206
	RD	Fresh Food		0.00102
	FP			0.00185

Appendix 4-30: Global Weighting Scores for the Lunar FARM Concept

Lunar FARM			**Total Score**	**0.51336**
Level 1	**Level 2**	**Level 3**	**Level 4**	**Global Weighting**
FC	LA	Partial		0.00227
	AIC	Semi-flexible		0.00210
	SCV			0.01121
	MS	Rigid		0.00267
	AGA	Shelves		0.01037
Level 1	**Level 2**	**Level 3**	**Level 4**	**Global Weighting**
EC	LT	Natural	Indirect	0.09166
	LS	Intracanopy		0.05748
	AtC	Enriched with CO2		0.11694
	TC	Per Growth Unit		0.03241
Level 1	**Level 2**	**Level 3**	**Level 4**	**Global Weighting**
AC	GM	Soilless	Hydroponic	0.10827
	PM	Monoculture		0.05935
	PS	Batch		0.00583
Level 1	**Level 2**	**Level 3**	**Level 4**	**Global Weighting**
IC	WP	Full		0.00206
	AR	Full		0.00206
	RD	Energy Food		0.00428
	FP			0.00441

Appendix 4-31: Global Weighting Scores for the BIO-Plex Concept

BIO-Plex			**Total Score**	**0.45348**
Level 1	**Level 2**	**Level 3**	**Level 4**	**Global Weighting**
FC	LA	Partial		0.00227
	AIC	Semi-flexible		0.00210
	SCV			0.01984
	MS	Rigid		0.00267
	AGA	Shelves		0.01037
Level 1	**Level 2**	**Level 3**	**Level 4**	**Global Weighting**
EC	LT	Electrical	HPS	0.00819
	LS	Overhead		0.02298
	AtC	Enriched with CO2		0.11694
	TC	Per Growth Unit		0.03241
Level 1	**Level 2**	**Level 3**	**Level 4**	**Global Weighting**
AC	GM	Soilless	Hydroponic	0.10827
	PM	Monoculture		0.05935
	PS	Combined		0.02916
Level 1	**Level 2**	**Level 3**	**Level 4**	**Global Weighting**
IC	WP	Full		0.00206
	AR	Full		0.00206
	RD	Quasi-Full Nutrition		0.01071
	FP			0.02411

Appendix 4-32: Global Weighting Scores for an Optimal Concept

Optimum			**Total Score**	**0.60430**
Level 1	**Level 2**	**Level 3**	**Level 4**	**Global Weighting**
FC	LA	Full		0.01047
	AIC	Flexible		0.00617
	SCV			0.02500
	MS	In-Situ		0.01719
	AGA	Shelves		0.01037
Level 1	**Level 2**	**Level 3**	**Level 4**	**Global Weighting**
EC	LT	Natural	Indirect	0.09166
	LS	Intracanopy		0.05748
	AtC	Enriched with CO2		0.11694
	TC	Per Growth Unit		0.03241
Level 1	**Level 2**	**Level 3**	**Level 4**	Global Weighting
AC	GM	Soilless	Hydroponic	0.10827
	PM	Monoculture		0.05935
	PS	Combined		0.02916
Level 1	**Level 2**	**Level 3**	**Level 4**	**Global Weighting**
IC	WP	Full		0.00206
	AR	Full		0.00206
	RD	Quasi-Full Nutrition		0.01071
	FP			0.02500