KARELIA UNIVERSITY OF APPLIED SCIENCES
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Mariia Smirnova

CONCEPT OF A SUSTAINABLE FOOD-GROWING UNIT ON MARS

Thesis
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Author
Mariia Smirnova

Title
CONCEPT OF A SUSTAINABLE FOOD-GROWING UNIT ON MARS

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Abstract

Present thesis relies on sustainable approach and the Innovative Conceptual Engineering Design. Concept development of a food-growing unit on Mars is a part of a challenge named “Sustainable Human Habitation of Mars” stated by NASA’s Epic Challenge Joensuu educational program. The thesis is a result of my collaboration with BioMars team that represents our vision on a food-growing system, which should be able to function independently beyond the Earth.

The project at hand was carried out according to the ICED methodology, which should require not only teamwork but also individual brainstorming and personal responsibilities. Thus, the current thesis should be considered as an outcome of activity within a field of design sustained by teamwork in terms of knowledge in engineering.

A concept idea of a food-growing unit was designed based on an implementation of algae and insect breeding as well as aeroponics as the main system for plant cultivation. The food-growing system was developed while taking into account Mars’ environment as well as In Situ Resource Utilization (ISRU) to sustain humans on the Red Planet.

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ICED methodology, problem-based learning, design, concept development, food-growing unit, Mars, sustainable approach, environment, In Situ Resource Utilization (ISRU), additive manufacturing, 3D modelling, algae, insects, potatoes, aeroponics.

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1 INTRODUCTION

1.1 Abstract

The present thesis is based on the development of a concept of a food-growing unit, one of the crucial parts of self-sustaining habitation on Mars. This project offered by Epic Challenge Joensuu, the educational program by NASA, aims to define a practical solution to a challenge named “Sustaining Humans on Mars – Habitat Design”. The thesis focuses achieving the goal of growing food independently beyond the Earth. The design of a food-growing unit should be made according to the special requirements of the unique Martian environment.

The accomplishment of this epic challenge needs enlisting the help of experts such as NASA’s specialists. Moreover, taking into account that the process of growing food on Mars should be considered as an extra ordinary problem, the development of a concept of a food-growing unit needs the teamwork required by the Epic Challenge Joensuu educational program. At the same time, the importance and necessity of the personal duties and the individual working process are highlighted.

As an outcome of the thesis, the developed concept of a food-growing unit should be regarded as the result of my cooperation with the multidisciplinary BioMars team. Together we should propose a practical and functional solution of a food-growing unit on Mars taking into account such methods as the Innovative Conceptual Engineering Design, the Building-Block approach and Intelligent Fast Failure capability. Thus, the present thesis project is the result of my personal activeness within a sphere of design controlled, sustained and enhanced by experts from NASA, coordinators at Epic Challenge Joensuu and teamwork. My personal duties as a designer and team member of BioMars should include the development of both structure and shape as well as the 3D modelling of a food-growing unit.

Being not a peer but a space amateur, I would like to introduce my thesis to readers as an easy to follow and interesting work, which contains some useful information and brings enjoyment. The current thesis shows my vision of sustainability regarding space-related architecture and design and represents my proposal for the conceptual design of a food-growing unit on Mars.

1.2 Exploration of Mars

As it is known, progress and technology do not stand still, and science never stalls. Our world moves on and humans keep improving on achievements and developing their skills. The history of space exploration is considerable. Not long ago humans walked on the Moon and today they make ambitious plans to colonize Mars.

Why Mars, and when it is possible? How can this become real?

Mars has the potential for expanding human presence. Scientists discovered that once there was life on Mars and there would be conditions suitable for human beings. Such important element for sustaining human presence as solid water has been found on Mars. Scientists believe that the exploration of Mars may help to find answers to unsettled questions about Earth (Wiles 2013).

The National Aeronautics and Space Administration (NASA) is leading humans towards the establishment of a permanent human presence on Mars that is perceived as an achievable goal. Through taking care of the next generation, developing a safe environment of a high quality of life beyond Earth, NASA thinks sustainably.

In working on achieving this goal, NASA is open for new partnerships, which can bring innovative ideas, define individual objectives, and develop technologies, techniques and systems. International collaboration aims to target the main focus – sustainable habitation on Mars.

2 LITERATURE REVIEW

2.1 Introduction to Literature

The current Literature Review aims to identify the key literature for my thesis. It is necessary to admit that due to the originality of the chosen topic, literature serves as the content basis for the thesis.

The goal of the present Literature Review is to determine the key definitions, requirements and limits of my thesis. Furthermore, the idea is to use a literature as a source of profound knowledge as well as for reasons of inspiration. However, it is necessary to note that the summary of the different arguments is one of the main preferences.

Supporting information for my Mars related thesis relies on searching for valid sources in the Internet, and a reference to the latest studies is required. The Literature Review holds various E-books and pdf, articles, websites and videos as well as information provided and suggested by the experts as a consultation and feedback.

Thus, the present Literature Review, based on valid scientific information, provides the facts and brings quality, exposes the key information and shows key sources, defines the limits to my thesis as well as helps to reach the requirements.

2.2 Thesis statement

The research question is “How would a sustainable food-growing unit on Mars, which could grow food Earth independently, appear and function?” This brings about the problem: “How should we grow food independently beyond the

Earth?" The result of the thesis, a sustainable food-growing unit on Mars, will be an answer for this problem.

2.3 Organizational method

It is important to note that the Literature Review addresses a description of the methodology used for the thesis and thereby expands not only a thesis framework, but also my entire working process on the concept development of a food-growing unit.

Thesis framework is based on the Innovative Conceptual Engineering Design (ICED) methodology, Intelligent Fast Failure, Building-Block Approach, teamwork, sustainable approach, 3D modeling, personal research and ideation as well as evaluation and analyses.

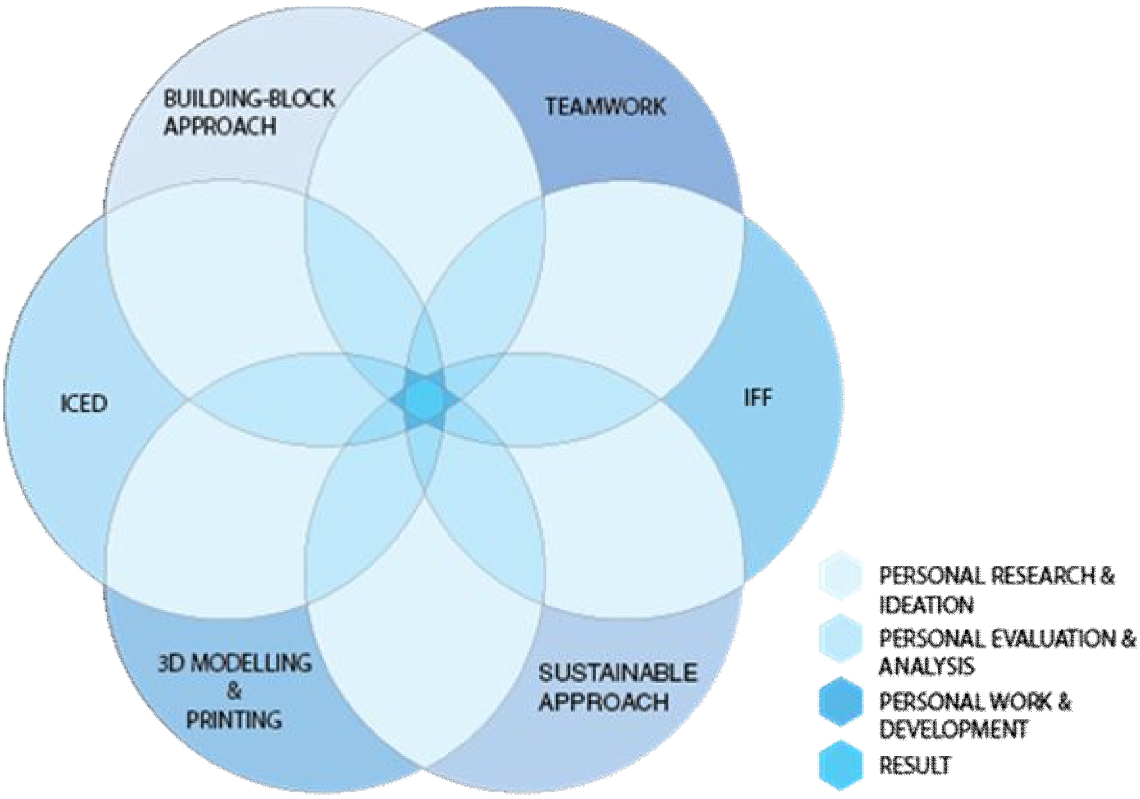


Figure 1. Scheme of thesis framework (by the author in 2016).

I have chosen a thematic organizational framework for my literature review that is supposed to be built around of the topic of my thesis. The literature review should be appropriate in terms of each stage of my working process on the thesis. Thus, the framework of the Literature Review is organized according to the framework of my thesis that relies on Innovative Conceptual Engineering Design (ICED). Looking ahead, I would like to note that the ICED, in turn, is based on a problem-based framework and project-based learning (Innovative Conceptual Engineering Design 2016, 11, 21).

2.4 Focus of the review

2.4.1 Abstract

A survey of the information is needed, for the consideration of the topic of my thesis relies on the following focal points:

- studies on Mars (including the features of Martian climate, environment, geology)
- information on a sustainable approach referring to Mars
- project requirements which form project constraints
- scientific research and existing solutions
- materials about ICED methodology used for my thesis

It is necessary to note that a sustainable approach as well as the project requirements relies on the researches of Martian nature; thus, from the holistic point of view, I will consider them simultaneously.

2.4.2 Innovative Conceptual Engineering Design (ICED)

The Innovative Conceptual Engineering Design (ICED) methodology was developed about 40 years ago by Dr. Charles Camarda, a NASA astronaut, Senior Advisor of Innovation and the man behind the Epic Challenge (Camarda, de Weck & Do 2013, 2). The ICED methodology was initially developed as an educational program for NASA's engineers to help them in searching for original and at the same time practical solutions to extra ordinary problems. The idea for the ICED methodology was defined during the working process of identifying the reason for the Space Shuttle Columbia accident and the ways to predict critical damages (Camarda et al. 2013, 3).

As is noted in "Innovative Conceptual Engineering Design (ICED) – Sustaining Humans on Mars" (2016, 22), ICED aims to solve multi-disciplinary epic challenges – complicated engineering problems, within an extreme environment, that have no perfect solution. This requires unconventional, creative and innovative approach. As it is admitted in the same source, the ICED methodology considers involving even crazy ideas (2016, 10).

As mentioned, since the methodology involves creativity, I would like to share my schematically done vision on it: Figure 2 represents the way I see the working process based on ISED.

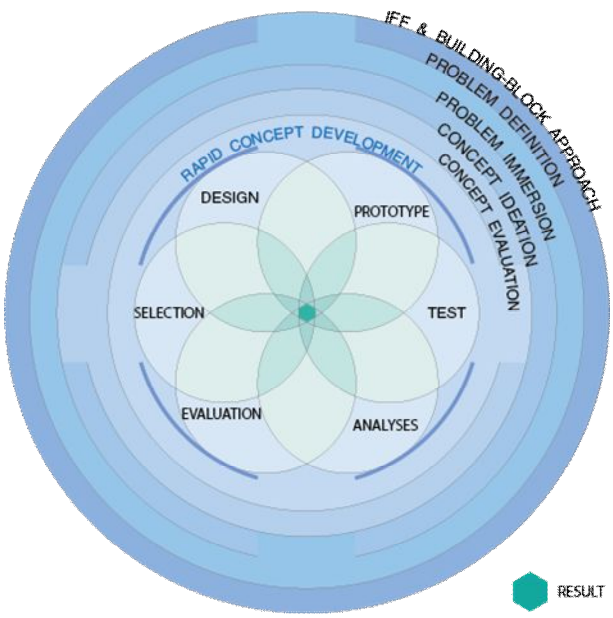


Figure 2. Author's interpretation of the ICED (by the author in 2016).

There are three main principles of ICED, which are pointed out in “Innovative Conceptual Engineering Design (ICED) – Sustaining Humans on Mars” (2016):

- ICED is developed to solve Epic Challenges
- ICED is based on the Building-Block Approach
- ICED considers the Intelligent Fast Failure (IFF) principle

The framework of the ICED contains three basic steps (see Figure 3):

- Team Learning and Knowledge Capture phase
- Creative Concept Generation phase
- Rapid Concept Development phase

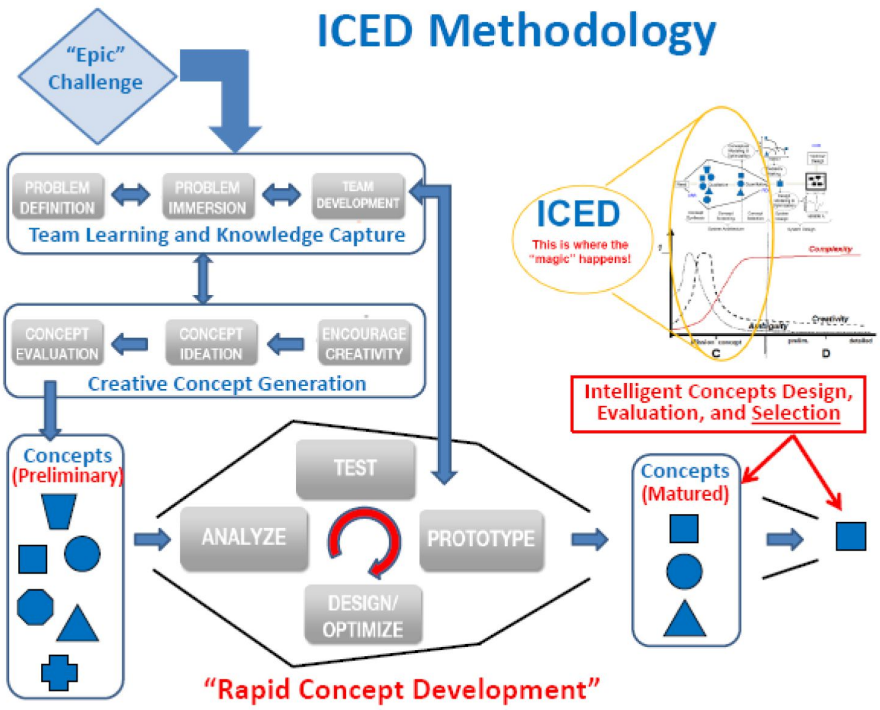


Figure 3. Schematic diagram of a framework for the Innovative Conceptual Engineering Design (ICED) process (Camarda et al. 2013, 3).

During on-line lectures via Adobe Connect as well as in the “ICED Return-to-Flight Example” video in the Internet, Camarda explained the structure and the main principles of the ICED methodology. Immonen took notes of the materials provided by Camarda and represented the bullet point in the pdf format named “1.3 Task details” (2015). The information below that includes a detailed explanation of each phase of the ICED based on the sources.

According to Camarda, **Team Learning and Knowledge Capture phase** includes three stages:

1. Problem Definition

This stage contains studying of the pre-defined problem definition: What is the problem?

2. Problem immersion

This phase implicates getting everything about the problem: learning and collection information, studying materials, items and tools, inspecting the challenge setup, individual brainstorming.

3. Existing Solutions

Googling existing solutions for similar problems as well as asking questions from the experts.

The team Learning and Knowledge Capture phase should be visualized through checklists, concept and mind maps. As the outcome of this phase, students are supposed to create:

- Problem Definition Concept Map

This is a representation of the fixed problem definition. What one should know about the problem?

- Existing Solution Concept Map

This is a recording of knowledge gained during Problem Immersion and Existing solutions stages.

- Check List for Critical Features

The checklist should contain the critical features of the solutions and parameters to be minimized and maximized. One can say that this considers project requirements.

The **Creative Concept Generation phase** is based on the ideation process and can be divided into three stages:

The first stage includes:

- The generation of multiple concepts using individual brainstorming technique in order to come up with possible solutions

- Presentation of ideas to share gained knowledge

The ICED concerns individual brainstorming and ideation process: each team member should develop numerous ideas separately and independently.

The second stage considers the rapid evaluation of each concept. The evaluation process should be carried out within a team through sharing thoughts and according to obtained knowledge, criticism and feedback from the experts. The third stage is focused on the selection of three or four of the best concepts for the next phase.

The **Rapid Concept Development phase** is the core of the ICED. The phase can be divided into two stages:

- Testing individual elements

- Testing full prototype

Finally, as an output of the Creative Concept Generation phase, three of the four preliminary concepts should be represented as sketches, simple illustrations or bullet points. The analysis and testing of the individual components is a crucial part of the ICED process. By testing the elements and details, one can make predictions, check them through small-scale experiments and hence avoid a failure of the full concept. This allows rapid experiments and fast failures of the small and basic elements of the complex concept. Based on results of the tests, failed components must be re-designed through the development and improvement of preliminary concepts. Experiments must be continued through re-tests of re-designed elements. Consequently, the two best concepts should be selected for the next step.

Moreover, following the principles of Intelligent Concept Design, Evaluation and Selection processes, this stage considers the analysis and testing of the full prototype in the same manner as described in the testing individual elements phase. The stage allows for the selection of a final concept.

Summary

ICED is required for the early phase of working process. As it is noted in “Innovative Conceptual Engineering Design (ICED) – Sustaining Humans On Mars” (2016, 11-12), the methodological focus on the conceptual design phase should be rapidly explored, discover, analyzed, learnt, considered and solved through modelling and prototyping, tests and experiments as well as fast failures. Moreover, the analysis-design-prototype-test cycle should proceed as quickly and productively as possible. The goal is to develop a great number of ideas simultaneously. This allows for obtaining a mature solution prior to a final decision. The final concept must not fail.

2.4.3 Research, engineering and design process by Dr. James Starnes

In order to eliminate a weak concept one should use the Research, Engineering and Design Process developed by Dr. James Starnes (Innovative Conceptual Engineering Design 2016, 18).

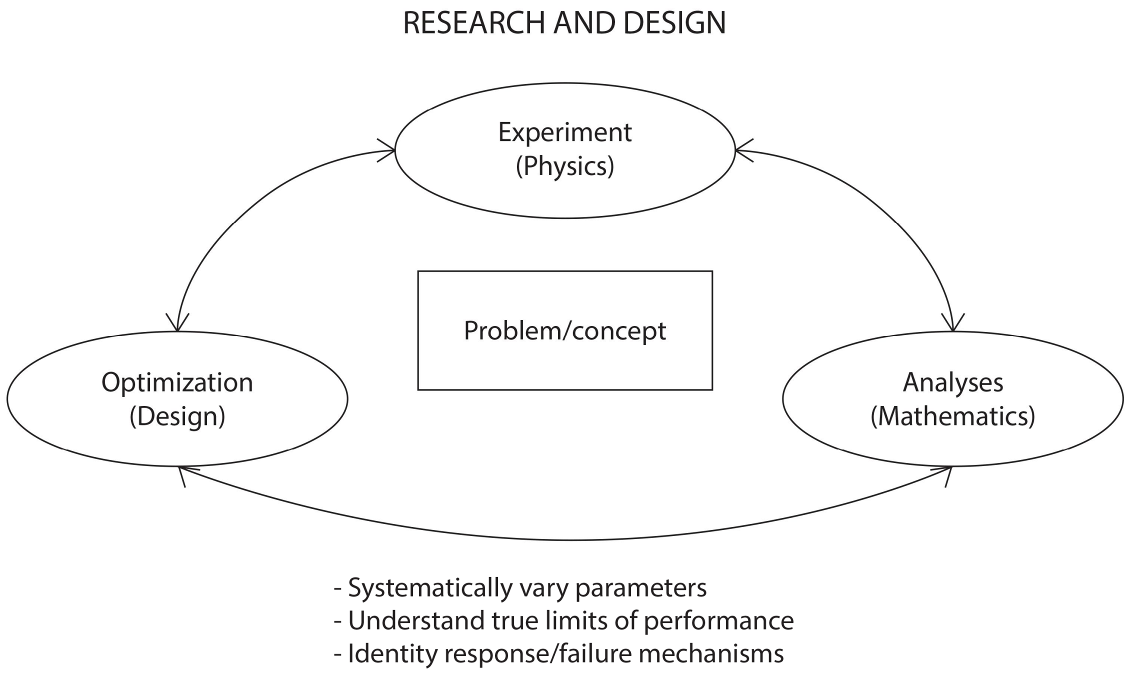


Figure 4. Schematic diagram of the research, engineering and design process according to Dr. James Starnes (Redrawn by the author in 2016. Based on Figure 1. Schematic diagram of the research, engineering and design process according to Dr. James Starnes in Innovative Conceptual Engineering Design 2016, 18).

The schematic diagram by Dr. James Starnes shows the relationship between analysis, design and testing and an infinite loop for the acquisition of knowledge. There is a process of obtaining of knowledge represented in the shape of a flat spiral. The way knowledge is gained lies in going over a great number of prototypes, tests, failures, discoveries, developments and improvements of the initial idea (Innovative Conceptual Engineering Design 2016, 8).

Research could be defined as the creative and diligent inquiry of a subject pursuing the purpose of exploration and discovery. According to the ICED methodology, research requires the consideration of existing solutions, theories and hypothesis (Innovative Conceptual Engineering Design 2016, 15). This intelligent approach aims to predict not only the behavior and results of the performances, but also when a concept will fail (Innovative Conceptual Engineering Design 2016, 17).

It is possible to note that a concept is a response to a problem one needs to solve, a consequence of design process. It is an initially selected starting point improved upon while optimizing and developing. Finally, a concept should fit design constraints and requirements determined by the problem (Innovative Conceptual Engineering Design 2016, 12).

According to Innovative Conceptual Engineering Design, an analysis is the perception affected by the capture of knowledge. Experiments are related to the testing of prototypes in laboratory (Innovative Conceptual Engineering Design 2016, 16-17). This is a verification of prediction through experiment and this may cause un-expected failures. The optimization phase is a consequence of failures.

2.4.4 Intelligent Fast Failure (IFF)

A capability such as Intelligent Fast Failure (IFF) enhances the efficiency of the ICED methodology. It is crucial to learn from failures, and in order to succeed failures must be explored as quickly as possible and prior to a final decision (Innovative Conceptual Engineering Design 2016, 24). It is important to learn how to fail on a small scale, quickly, cheaply and as early as possible in order to achieve success. Quick fails enhance rapid gains in the learning process. Intelligent Fast Failure aims to achieve a satisfactory under-standing in the shortest time.

Numerous trials lie behind an intelligent decision and final selection. One must test the limits of a theory to make a real observation and explore sufficiently (Innovative Conceptual Engineering Design 2016, 17). This leads to a fundamental understanding of a problem.

2.4.5 Building-block approach

This is an advanced way to explore a given subject. According to the building-block approach or the stepwise, it is necessary to divide complex model into subcomponents or simplify matters to an elemental level to achieve basic principles of initial design through small-scale tests and simple experiments (Innovative Conceptual Engineering Design 2016, 19). This is a quick, easy and relatively inexpensive way to check for witnesses of a theory and failures.

2.4.6 Essential needs and sustainable approach

The topic of the present thesis concerns the challenge of sustaining humans on Mars Earth independently. According to the ICED methodology, an environmental control and life support system (ECLSS), and a food-growing unit as a part of it, should be sustainable (Innovative Conceptual Engineering Design 2016, 12). Therefore, in order to develop a solution, it is necessary to take into account sustainability and its approach in terms of economic, social and environment issues. Hence, the main goal of a sustainable approach is long-term care about the essential needs of the Martian settlers corresponding to the available resources.

What are the preliminary demands of humans on Mars? There are some obvious things such as food and water, breathing air, habitability, safety and health. This leads to the hidden, at the first glance, but no less important issues such as a diet on Mars as well as creating and maintaining the required conditions for food growing and food storage. Thus, it is crucial to consider not only human needs, but also the Mars-related features of demands that may occur.

As it is known, price matters. Economic sustainability concerns local food production possibilities for permanent settlement on Mars. There is no doubt that a continuous meal supply should be assumed as one of the most crucial human demands. One should note that in-situ food production in such an extreme environment as Mars has is costly, especially during the first years of establishing a

Mars settlement. However, a food supply from Earth is possible, but its price makes this inappropriate. According to Turnbull (2014), one kilogram of cargo to Mars would cost about $7,000 – 10,000. Russon (2014) provides different numbers: from $10,000 to $100,000 would be the price for a kilogram of food supply.

In addition to price, how long does it take to get Mars? Redd (2014) states that an Earth-Mars journey takes on average about 162 days. At the same time, Cain (2013) specifies pointing out that to reach Mars one needs 150 – 300 days; and that depends on many factors. Once every two years there is a close distance between Earth and Mars, about 56 million km, and the travel time still depends on the position of the planets (Redd 2014). As Boyle (2013) puts it, every two years for a few weeks there is a Mars solar conjunction when Mars and Earth are positioned on the opposite sides of the Sun. In addition, Turnbull (2014) notes that there is a gap of 26 months for an Earth-Mars cargo supply. Taking the above-mentioned into account, the importance of in-situ Earth independent food production on Mars becomes apparent.

Besides the cost of food delivery, the time it takes and the frequency of sending, it is necessary to assume the health benefits of natural food, which is totally preservative-free or contains as few chemical preservatives as possible. It is self-evident that food is a perishable subsistence and it is not possible to deliver fresh food to Mars. Humanity invented different ways to store food, but long-term food preservation does not allow keeping all the vitamins. The production of fresh and healthy food is necessary for Mars settlers. As it is known, humans in space need nutrient-rich food and proteins; it is a matter of life. It is crucial to keep an optimal fat-muscle ratio. Being in a long-term state of weightlessness causes muscle weakness. Wall (2010) notes that a journey to Mars could convert a 30-50-year-old astronaut to a person with the performance of an 80-year-old. To prevent muscle loss an astronaut needs not only routine physical exercises but also a balanced high-protein diet. That is why the in-situ production of high protein and nutrient dense food is of primary importance.

In order to understand how to grow food on the Red Planet, it is necessary to consider the features of environmental sustainability. From the beginning of Mars colonization, it is important to focus on the given site and available resources, considering specific features and potential issues. Passive and active design strategies such as, for instance the implementation of renewable energy resources, should be taken into account.

It is crucial to remember that the focus should be given, inter alia, to humans. According to the ICED methodology, along with the Martian environment and human physical issues, one should regard psychological and physiological problems (Innovative Conceptual Engineering Design 2016, 12). Thus, it is essential to think not only about human survival needs, but also about his or her state of mind. By living in an extreme environment and missing wild nature on the native planet, Mars settlers will need a change of atmosphere. The quality of living is a crucial factor of social sustainability. It is necessary that an internal environment of Martian habitat should be healthy and comfortable. At this point, plants can play a significant role in social sustainability, bringing a sense of well-being and, in addition, offering psychological treatment (Herridge 2015). People are social creatures. Humans seek friendly interaction and sharing activities. On one hand, gardening can gather Martian settlers together. On the other hand, a relaxing atmosphere during private time for the cultivating of plants offers a calming effect and aims to relax. The availability of fresh food can cheer up settlers surviving in the extreme Martian environment. What are the things a human get out from the interaction with a plant? After being in contact with different machines and robots, they can get rid of stress by enjoying the green environment around them. People will smell the plants; inspect changes with growth factors and the changing of colors.

As mentioned in the beginning of the chapter, it is crucial to assume simultaneously social, environmental and economic sustainability (Zabihi, Habib & Mirsaeedie 2012, 1). The sustainable approach relates to the development of a suitable, healthy and safe environment for future generations on Mars. Therefore, one should not only sustain humans on Mars, but also provide a comfortable atmosphere.

2.4.7 Project requirements

The project requirements for my thesis draw upon the scientific discoveries, recommendations, notes and remarks as well as different constraints defined by the space-related specialists. The requirements should take into account a sustainable approach that is considered regarding existing data and researches on Martian issues.

A food-growing unit is a one of the essential parts of the Martian habitation system. The design concept of a settlement must consider food production. According to Anderson, Finger, Lantz and Theno (2015, 1), it is required that from the first mission on Mars crew members should develop plant growth that is considered as bioregenerative life support for food production, primary water purification and atmosphere revitalization. Besides, Trotti (2007, 2) proposes utilizing an autonomous and automatic smart system. For instance, such a self-sustaining system could control the growth of plants prior to arrival of the first human as well as while all the crew members outside a settlement explore Mars. In addition, as Bushnell and Moses (2015, 27) note, an autonomous system does not require a salary.

The design of a food-growing unit must be fault tolerant to control critical and catastrophic hazards. Anderson et al. (2015, 8) state that the unit should be resistant against an injurious effect of galactic cosmic rays (GCR). In addition, it is crucial to consider solar particle events (SPE) that are harmful to human health (Innovative Conceptual Engineering Design 2016, 12). Bushnell and Moses (2015, 20-25) suggest that an underground position of a food-growing unit should be estimated as beneficial regarding thermal, micrometeoroid protecting and radiation shielding. Moreover, Bushnell and Moses (2015, 20-21) believe that, in terms of sustainability, usage of lava tubes in the regolith could decrease development costs. Thus, the concept design of an underground food-growing unit (under at least 5 meters of regolith) should be defined as the least effort inducing and lowest cost solution (Bushnell & Moses 2015, 20). Martin-Brennan and Wheeler add that the underground positions of Martian caves provides not only higher than above ground atmospheric pressure, but also geothermal energy (2000, 10).

Technical constraints, critical design requirements, standards and regulations should be taken into account. To meet international requirements and in order to decrease production costs, a habitation system is supposed to be designed to increase logistical efficiency as well as to improve maintenance capabilities (NASA’s journey to Mars 2015, 22). Maintenance needs should be reduced. According to Anderson et al. (2015, 9), the maintenance operations should be quick, easy and simple to operate to decrease the workload for crew members. It must be serviced by a limited number of crew members consider the usage of the restricted equipment and tools. In addition, the existing technologies and physical processes must be used to lower costs and technical risks.

The food-growing unit should be designed taking into account cost and weight issues: reducing the payload weight and stowed volume is crucial. According to the ICED, damage-tolerance as well as being lightweight are important parameters for design development on Mars (Innovative Conceptual Engineering Design 2016, 8, 12). Notably, NASA assumes lightweight inflatable structures as reliable for used on Mars. Inflatable structures have some benefits such as relatively low cost, compact storage and comparably small transport mass-volume ratio as cargo (Martin-Brennan & Wheeler 2000, 31-32). In cases of using natural caves on Mars for underground greenhouses, inflatable membranes could be a suitable solution. In addition, Anderson et al. (2015, 8) highlight that the shelter structures must be safe when considering robustness, durability and the capability to sustain damage without breakdown. The early implementation of the In Situ Resource Utilization (ISRU) approach as well as In-Situ Manufacturing or Additive Manufacturing (3D printing technology) relies on economic sustainability and offering the potential to decrease risks and costs, since 3D printers produce long-term effects and spare details (Bushnell & Moses 2015, 15).

Materials used for food-growing unit must be recyclable afterwards and produced using the enable resources on Mars according to In Situ Resource Utilization (ISRU) (Bushnell & Moses 2015, 1). Materials produced on Mars should be for long-term usage. The food-growing unit should last a minimum of a couple of years prior to the arrival of the first colonizers. According to Martin-Brennan and Wheeler, high resistance against ultraviolet light is appreciated (2000, 28). Besides, some parts of the growing unit should be made of materials with high transmittance to provide enough light.

It is important to collect as much natural sunlight as possible and guide it from the Martian surface to the underground greenhouse. Bushnell and Moses (2015, 16) state that an underground food-growing unit requires efficient and effective lighting that contains not only an implementation of an artificial light, but also a design solution for the provision of daylight. Moreover, solar energy should be assumed as an essential way to reduce energy consumption (Martin-Brennan & Wheeler 2000, 31-32). This can be defined as a sufficient sustainable approach. I believe it would be ideal to develop a passive strategy for the transmission of sunlight to the plants cultivated in a food-growing unit.

Moreover, the placement of a food-growing unit should be considered. In addition to the previously mentioned issues regarding the underground location, it is necessary to note that a food-growing unit should be designed as a separate zone from the livable human habitat. At the same time, the unit must have a direct connection with food storage, water reservoirs, storage for oxygen and carbon dioxide (Anderson et al. 2015, 36).

Based on the ICED methodology that was developed to solve epic challenges in an extreme environment (that is applicable to Mars), the life support system should be robust and reliable (Innovative Conceptual Engineering Design 2016, 12). This refers to sustainability and highlights the importance of a holistic approach to Mars related design development.

2.4.8 Existing solutions

While developing solutions for the problem of food, it is crucial to take into account the essential needs and project requirements, sustainable approach and in-situ resources on Mars for the purpose of growing Earth food independently. Besides, following the ICED methodology, it is crucial to learn from the past as well as to become experts on the existing solutions in order to be able to predict failures (Innovative Conceptual Engineering Design 2016, 15, 22).

Human essential needs

High protein and nutrient dense food

The food-growing unit should provide enough nutrients and proteins in order to meet requirements for a Martian diet. The challenge is that it must be not only a continuous, but also a fast process. So, which plants to be grown on Mars should draw attention? What should be the best source of protein on Mars?

Plants growing on Mars should be low-maintenance, fast and easy to grow, and nutrient-rich. Plants should be able to grow in a limited area. At the same time, high-yield species with great ratio of edible parts are preferable.

Potatoes can be selected as a good source of energy, carbohydrates and protein. In addition, the crop contains vitamin C and microelements such as zinc and iron (Dube 2016). NASA notes that potatoes can be a proper choice for sustaining people on the Red Planet since this crop can withstand cold conditions and grow in low-pressure (Dube 2016). Thus, potatoes have a chance to survive on Mars. Moreover, NASA believes that potatoes can be grown in situ on Mars under the automatic control of robots prior to the arrival of the first colonizers. According to Dube (2016), NASA conducts experiments on growing potatoes in desert dirt. Burrows (2016) adds that currently NASA’s researches conduct the experiments checking out which type of potatoes would suit Martian conditions the best.

Besides the vegetable protein that a Martian diet could be enriched with, insects should be considered as a primary source of animal protein. According to

Bushnell and Moses (2015, 12), insects could be assumed relevant for the Martian diet. The infographics in Figures 5 and 6 represent insects from a sustainable point of view as well as explain why, for instance, crickets should be a proper choice.

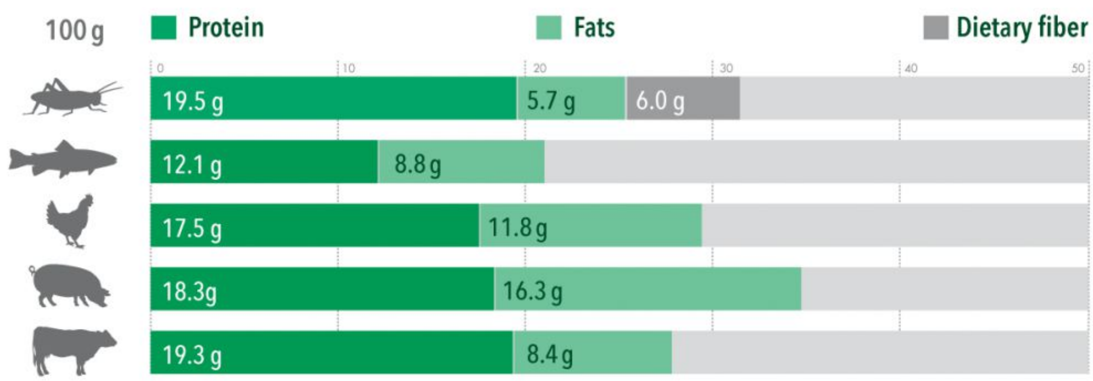


Figure 5. Nutrient chart (EntoCube 2016).

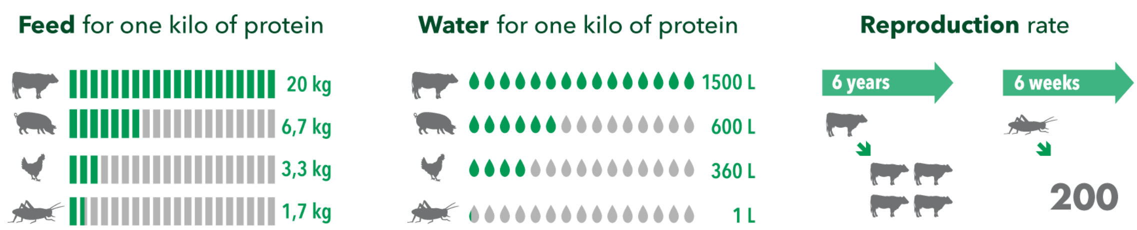


Figure 6. Input and output (EntoCube 2016).

The Finnish insect farming company EntoCube (2016) sees insects as a highly nutritive meal. Moreover, EntoCube (2016) considers insect breeding as a sustainable way of food production.

According to EntoCube (2016), the company uses regular shipping containers of different sizes and layouts. The growing system by EntoCube considers a different internal climate depending on different insect species. Although the current system is robust, EntoCube believes that automating the process will decrease manual labor and increase the outcome as well as allow for the development of a large-scale system (EntoCube 2016). Figure 7 shows the technology used by the company.

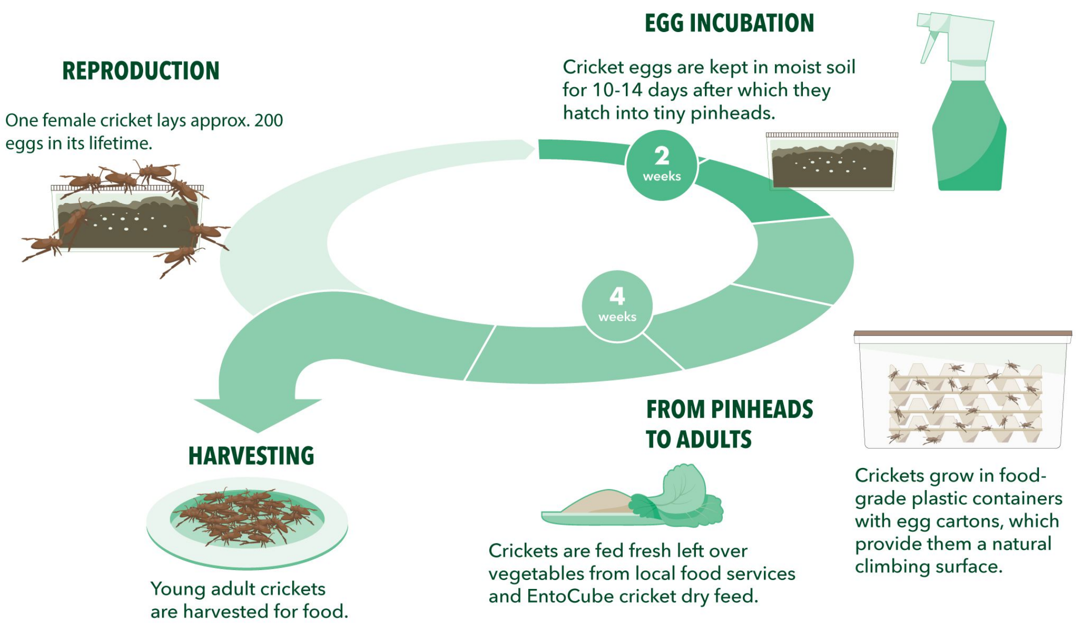


Figure 7. Process of growing of crickets (EntoCube 2016).

According to the result of the survey conducted by the BioMars team, after people tasted bugs, their positive attitudes towards eating insects increased dramatically (Holappa, Korhonen & Kuokka 2016). However, it is important to avoid a meal looking uninviting. The purpose is to make insect dishes a delicacy, more appetizing and tasty-looking for Martian occupants. The usage of insect powder that, according to EntoCube (2016), contains 70% protein should be a great solution. NASA develops this issue further by considering implementing 3D printing for cooking on Mars; and insect- as well as algae-based powder can be assumed as a basic material (Templeton 2013). However, in spite of the protein-rich features, not only appearance, but also any contact with bugs may be repulsive. That is why it might be significant to prepare a course of therapy against entomophobia or insectophobia to adapt the colonizers of Mars. This should take some time. However, in the future humans on Mars should raise a new generation resistant to fear of the bugs.

If it should be possible to cook insects in space, would it be possible to breed them on Mars? Some researchers believe so. China expands on the idea of insects for space agriculture. As Russon (2014) puts it, the Chinese project called Yuegong-1 or Moon Palace-1, Permanent Astrobase Life-support Artificial Closed Ecosystem, was developed in order to test the features of plants and insects growing on the Moon as well as an applying its results for human consumption. Notably, worms are assumed as the main source of protein in the Chinese space diet. Besides plants growing in soil and bugs, Chinese scientists breed microorganisms and animals in the laboratories at Moon Palace-1 (Chinese space team 2014). This controlled ecological life support system relies on a principle of bio-waste, water and air recycling. Moon Palace-1 considers plant and insect farming in the self-contained laboratory, which was developed as a sealed capsule (Chinese space team 2014). In spite of the fact that Moon Palace-1 simulates an Earth-based environment, Chinese researchers believe that their bioregenerative life support system should be suitable for a Martian base.

Algae have been mentioned for a reason. The point is that algae provide an abundance of nutrients: eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), omega-3 fatty acids as well as some minerals such as magnesium, iodine, calcium (Andrews 2016). Thus, algae might be an extremely important species in Martian settlers' diet and would be able to support human health. The nutrients that algae produce are important for both children's and adult's health condition, immunity, mood, nervous systems, mental development, aptitudes for learning and memory, vision, cardiovascular function (NASA). Therefore, it is crucial to consider algae as one of the main elements in a food-growing system on Mars, especially in the case of raising up a new generation of Martian habitants.

Oxygen

Besides food production, to sustain creatures on Mars it is vital to produce enough oxygen. As it is known, plants are not only a source of food, but also a crucial element for replenishing the air and water purification. The plants which would grow in the Martian greenhouses would produce oxygen but not as efficiently as algae could do. Therefore, using plants, no matter how many of them, as the only oxygen producers on Mars would maybe not be sufficient to survive.

Like other plants, algae use photosynthesis; these little cells capture carbon dioxide and, according to Hall (2011), algae generate about 70 - 80 percent of oxygen in the Earth's atmosphere. Based on the research done by the Monterey Bay Aquarium Research Institute (2010), algae need light and nitrates to grow. As it is known, nitrates contain nitrogen (Difference between nitrogen and nitrate 2011). Algae are able to grow taken nutrients from wastewater and carbon dioxide from the atmosphere (Marlaire 2009a). At the same time, Wentz (2015) states that algae should be able to produce oxygen from nitrogen that is in the Martian soil. Currently NASA conducts some experiments on growing algae in agar in a microgravity conditions (Wildenberg 2016). The reason why NASA's researches have chosen semisolid agar instead of liquids as a growing medium is that agar is easier to control in weightless environment.

Keeping in mind the information mentioned above, one can conclude that the cultivation of algae on Mars can bring not only nutrients, but also such benefits as water purification, fertilizer and biomass, oil and biofuel production (Marlaire 2009b).

Plants essential needs

Growing conditions

How could we cultivate plants in the Martian low-gravity environment and what are the issues of this? According to Owen (2012), plants can grow and even flourish in a weightless environment, and gravity does not guide these. Plants normally grow toward light and their roots orient towards sources of water and nutrients. Thus, microgravity should be suitable for Martian plantations. There should be no need for any great transformation of the environment. This brings into consideration of the in-situ approach and the ways to enhance environmental sustainability on the Red Planet.

Besides environmental issues, it is crucial to define what should be the most convenient process of growing plants on Mars. According to Dube (2016), NASA considers cultivating potatoes by aeroponics or hydroponics. In order to grow plants, one needs water, nutrients and carbon dioxide. As Toothman (2008) states, weightlessness and low pressure cause the scattering of water and allow delivering airflow to the roots of plants. Therefore, the usage of a hydroponics or aeroponics system is reliable.

Hydroponics and aeroponics are quite similar. At the same time, one can note that aeroponics has some advantages. A hydroponics system delivers nutrients to plants in water, while aeroponics – in air as a mist sprayed inside a growing unit. A hydroponics system contains an absorption material such a foam, hydroton or gel that provides a growing medium, absorbs some water and nourishes plants (Hydroponics 2016). Aeroponics does not require any substrate; thus, it excludes the additional weight of a growing medium. Moreover, plants that grow by aeroponics are easy to transplant. Both systems aim to conserve natural resources such as water, but aeroponics save space inside a greenhouse allowing plants to grow vertically.

Lighting

Besides microgravity and atmospheric pressure factors, one should consider that plants need efficient lighting, preferably sunlight or an artificial source of light of full-spectrum. In this case, a full spectrum light-emitted diode or LED is a good alternative. According to researches, plants need mainly red and blue light (Grow light 2016). In addition, regarding a sustainable approach, it is important to select an energy-efficient and power conserving source of light due to the lack of energy resources on Mars.

It is worth considering the sufficiency of providing of natural light to an underground food-growing unit in terms of sustainability. In fact, this is a specific challenge that should be solved. In this case, a hybrid lighting system implementing fiber optics and light-emitted diodes (LEDs) has potential. In my opinion, an installation of solar cells and radiators as well as photovoltaic panels (PVs) as a source of a renewable energy is a profitable way to reduce demands for electricity generation.

2.5 Reliability and ethics

The Literature Review brings up what is known and what should be discussed and concerned. This involves matters of ethical issues, for instance, in terms of the exploration of Mars.

There are many discussions in mass media on Mars and its challenges. Mentioning debates on Mars it is possible to highlight three crucial categories: money issues, sustainability and a human approach. One may raise such typical questions as follows:

- Is the exploration of Mars worthy of the investments it needs? (Walker 2016). In this case, I would ask why one spends money on Martian issues when there is starvation on Earth?

- Why is there a desire of terraforming Mars while there are so many challenging environmental problems on Earth? (Green 2015).

- What are the social impacts of establishing a colony on Mars? (Stemwedel 2015).

On the other hand, NASA's Chief Historian Steven J. Dick (2007a) asks "…is it ethical NOT to explore?" Essentially robotic and human space expansion and discovery – all of this is a question of time. The most crucial thing to be considered is the consequence of exploration.

In my opinion, NASA thinks globally and looks forward to creativity, innovation and development. Mars One and Mars Exploration Program consider the long-term perspective of human future. According to Dick (2007b), one of the main arguments for exploration is human self-preservation. One should not equate the colonization of Mars with conquest (Dick 2007a). I would say that the exploration of Mars refers to the holistic approach to sustainability. This might be the possibility to learn from the challenges of Mars, for instance, to develop skills and knowledge regarding environmental issues. The experience gained from the exploration of Mars would bring a fresh view of accustomed things.

However, it is necessary to note that I am not an expert in space-related sciences and unable to give constructive criticism. At the same time, having knowledge of a sustainable approach, I would like to consider the challenges of growing food Earth independently from a sustainable point of view. Further, as an architect, I would like to pay attention to the project requirements that a food-growing unit on Mars should have. In addition, in my opinion, it is crucial to take into account not only the technical aspects of the project and requirements for the growth of plants, but also human needs, since sustaining humans on Mars is the main challenge of Martian colonization. The above-mentioned topics narrow a scope of my thesis and studies on the chosen subject.

To sum up, I would like to quote a saying of Dick (2007a): “I hope the choice is to move forward into space with all the vigor we can summon, while taking into account the consequences using the lessons of history”.

2.6 Epilogue

The subject of the thesis relates to sustaining humans on Mars. The conceptual development of a food-growing unit aims to define a solution of a food growing Earth independently. This requires the consideration of the engineering issues, design development, implementation of the technical knowledge as well as co-operation with the experts.

It is necessary that the Literature Review draws upon the latest scientific researches, innovative methods and solutions, technologies, discoveries and developments in the field of space exploration. At the same time, it is crucial that not all of sources of information are proved. Some materials are still represented as a scientific guess, which might be confirmed or refuted. However, the Literature Review can be assumed as a source of information to find existing solutions that could inspire me and guide towards an understanding of the necessary suggestions and requirements.

It is possible to note that the present thesis can be considered as a practice-based review since it relies on problem- and project-based ICED methodology. According to the ICED methodology, the present Literature Review can be assumed as a part of Team Learning and Knowledge Capture, since it contains learning materials about the subject of the thesis, searching for the related information, made researches and existing solutions for similar challenges. Moreover, one can note that the Literature Review not only organizes the found materials according to the subjects, but also creates a basis for the thesis structure as well as providing background knowledge for the Creative Concept Generation phase.

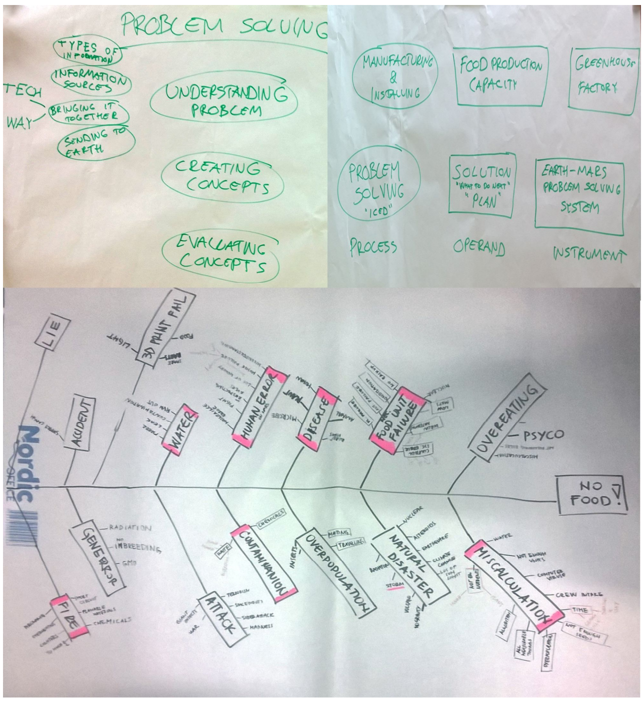
Besides, I would like to admit that since the working process contains the experiments and tests under supervision as well as the feedback from the coordinators and experts, the thesis could be defined as a valid study with reference to the moment when it is completed. Therefore, there is the inherent likelihood of further development.

3 DESIGN PROCESS

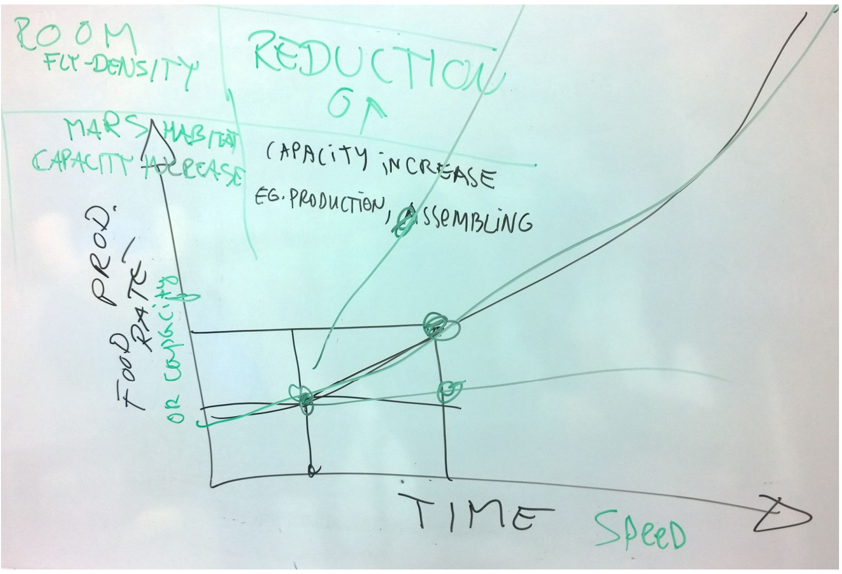
3.1 Abstract

Epic Challenge Joensuu started with learning of the ICED methodology, Building-Block approach and Intelligent Fast Failures, as well as participating and leading some workshops in order to train, enhance subject related knowledge and learn from gained experience. Furthermore, at the Team Learning and Knowledge Capture phase, following the ICED education structure, my BioMars teammates and I were studying Mars facts and relevant challenges, researching existing solutions, preparing and discussing lessons in order to pre-define the “sustaining humans on Mars” subject and learn about the problem of food growth. The goal was to understand what we should know about the challenges we were supposed to work with and what could be solutions. In other words, we were able to find different ideas, which could help us with concept creation.

As a result, a problem definition concept map was made. This allowed us to create not only an existing solutions concept map, but also a checklist for critical features of the solutions and parameters to be minimized and maximized. It was assumed that the time issue should be maximized and the money issue minimized. For instance, the working lifespan of an operational support system of a food-growing unit on Mars should be maximized, and its cost should be minimized. Another example is this: as time goes by, food capacity or food production rate should increase (see Picture 2).



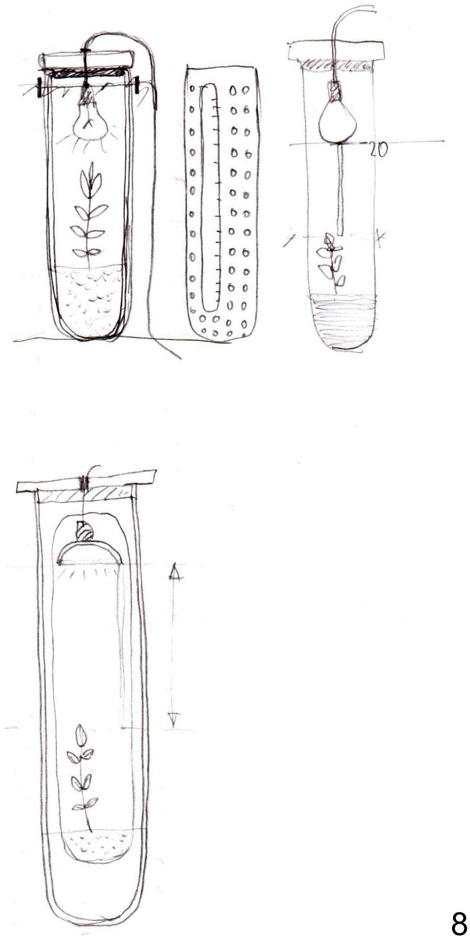
Pictures 1. Sketch ideas for Problem Definition, Problem Immersion and Problem Solving concept maps (by BioMars team in 2015).



Pictures 2. Critical feature. Sketch (by BioMars team in 2015).

While obtaining team communication skills and problem related knowledge, we moved on to the Creative Concept Generation phase and began to work on concept ideation and concept evaluation. Each of the team members was able to propose at least ten ideas as a result of individual brainstorming (see Figures 1–4 in Appendix 1). All ideas were discussed among the team members in order to come up with possible solutions to our problem. Proposals such as insect breeding and diet in space, fiber optics and "growtube" were evaluated as potential preliminary concepts. Thus, these ideas were selected to be developed further.

Pictures 3. Concept ideation (by BioMars team in 2015).



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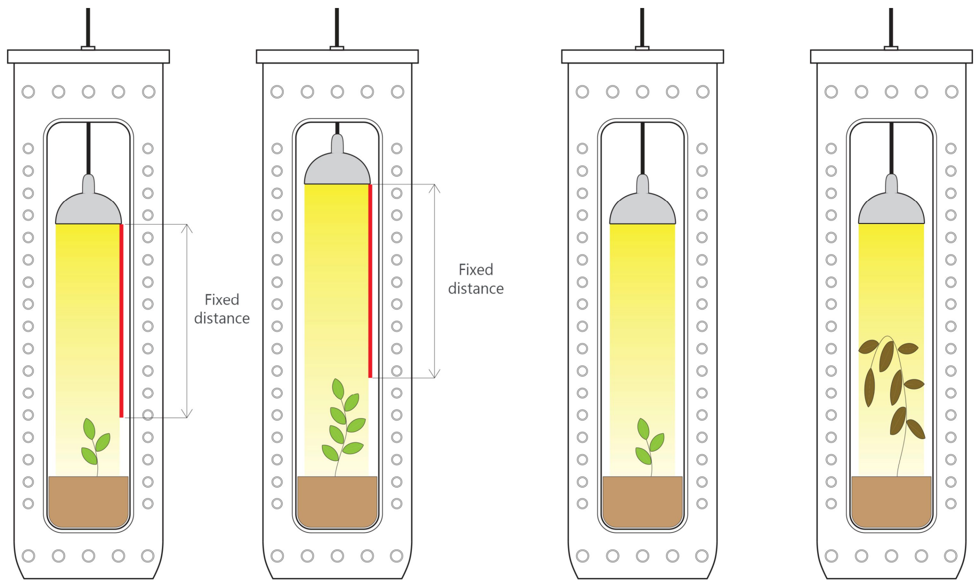


9.

Figures 8, 9. Growtube (Idea by Pölönen in 2015-2016; developed by Soloveva & Smirnova in 2016. “Constant distance” idea by Soloveva & Smirnova in 2016; consulted by Gebejes, Karhu & Ilo in 2016). Sketches and graphical illustration (by the author in 2016).

Initially the BioMars team considered the Growtube concept as an individual plant growing tube intended only for a single plant (see Figures 8 & 9). The concept was proposed in order to define a solution, which allows growing food effectively. According to Martin-Brennan and Wheeler (2000, 32), one should minimize losses between plant and the source of lighting. At the same time, it is important to keep a reasonable distance between them. That is why the flexible position of the source of light should allow keeping a constant optimum distance between plant and LED lamp. It was estimated that the constant distance should be better for plant growth rate than the varying distance. This solution should eliminate the harmful factor of hot and dry air produced by LEDs. Consequently, that would prevent the drying of a plant. Thus, this artificial light source was estimated as an effective solution for plant growth. In addition, it is to be noted that Martian soil was considered as a plant-growing medium.

According to the concept, increasing the number of Growtube units would provide flexibility: each unit could serve individually regarding the requirements of different plants. In addition, individual units would allow Mars settlers to keep more plants alive in case of disaster. Although one could assume Growtube as robust and applicable regarding the ISRU, the in-situ development of a single Growtube for a single plant would be costly. Thus, according to economic sustainability, the concept was estimated to be unprofitable.

However, above mentioned ideas were developed during the Rapid Concept Development phase. The Growtube concept was regenerated into a growing chamber designed for four plants that, in turn, affected my design proposal for the plant-growing unit. The insect farming and diet idea turned into one of the main principles for our food-growing system.

According to the Building-Block Approach, several simple tests of individual elements, based on the selected concepts, were conducted prior to the final solution in order to understand the principle and “prove” the hypotheses that lay behind them. According to the Research and Design approach by Dr. Starnes, after the first results were obtained and rapidly analyzed, some experiment (for example, tests of various fiber optics in a laboratory) was re-done until the time when it became possible to predict its performance. The results of the experiments were considered to predict the consequences of possible failures as well as to indicate the probable weaknesses, which must be improved regarding project requirements. Although some tests failed, they were performed according to the Intelligent Fast Failure approach. Due to the time limit we had, it was important to learn efficiently from our mistakes prior to the final decision being made.

It is necessary to note that at the time of writing the thesis, two full prototype experiments are not completed and the final prototype is not ready. However, the current chapter of my thesis contains all necessary information needed for understanding my design proposal for the concept of a food-growing unit.

3.2 Principles of food-growing system

Generally, the food-growing system should be simply explained as an aeroponic system for a plant-growing unit with a supplementary part for the growing of algae and an insect-growing unit attached. It should be noted that aeroponics was considered as a reliable system for potato cultivation on Mars.

As it is known, carbon dioxide and oxygen gas exchange facilitates photosynthesis. Plants, as a crucial part of life support system on Mars, should recycle carbon dioxide exhaled by humans and, in this case, by insects as well. Excess of oxygen, produced by plants, could be stored. In turn, insects would consume oxygen and produce carbon dioxide. In addition, insects would produce a scat that could be used as a fertilizer for plants. Moreover, insect should be taken into account due to their ability to convert inedible parts of vegetation into animal protein. One can note that comparing with, for example, livestock rearing, breeding insects should be relatively simple and fast. The insects should be characterized by quick reproduction rates and short life cycles that would allow for stable and continuous harvesting. Their extremely small weight per organism would be beneficial as cargo in terms of delivering them to Mars.

Accordingly, the plant- and insect-growing system would also provide recycled food, water and nutrients, keep air exchange, and recover these natural sources back into the system. Theoretically, this system could be developed into a closed ecosystem.

15.4.2016 my BioMars teammates and I got the chance to represent our concept to Dr. Camarda during a live call. We were speaking about the principles of our food-growing system. It is possible to note that we got positive feedback. According to Dr. Camarda, on the one hand, insects have not been considered as a part of Martian diet and a food-growing system on Mars (Camarda 2016). On the other hand, it might have potential. In addition, Dr. Camarda noted that it would be challenging to manage and control a closed ecosystem, since the system should be able to operate autonomously and produce everything it would need by itself. It is necessary to note that, according to our concept, the food-growing system on Mars should consider a set of small-scale growing units that would be easier to control. Thus, our concept could be taken into account.

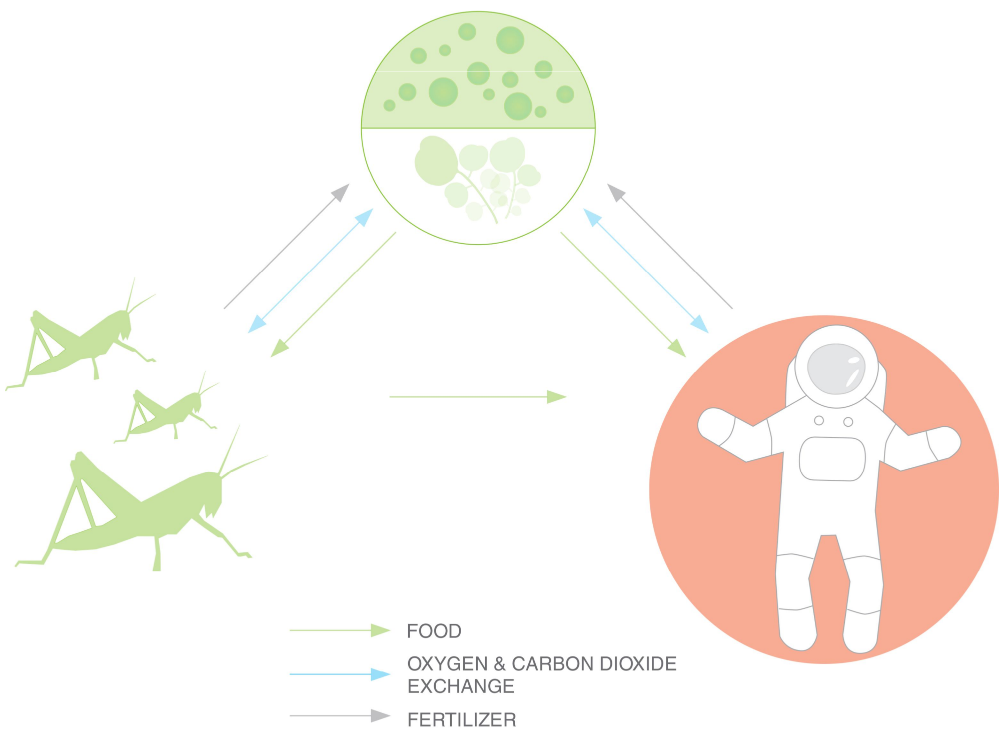


Figure 10. Principles of the food-growing system (by BioMars team in 2016). Graphical illustration (by the author in 2016).

3.3 Creative process and design ideas

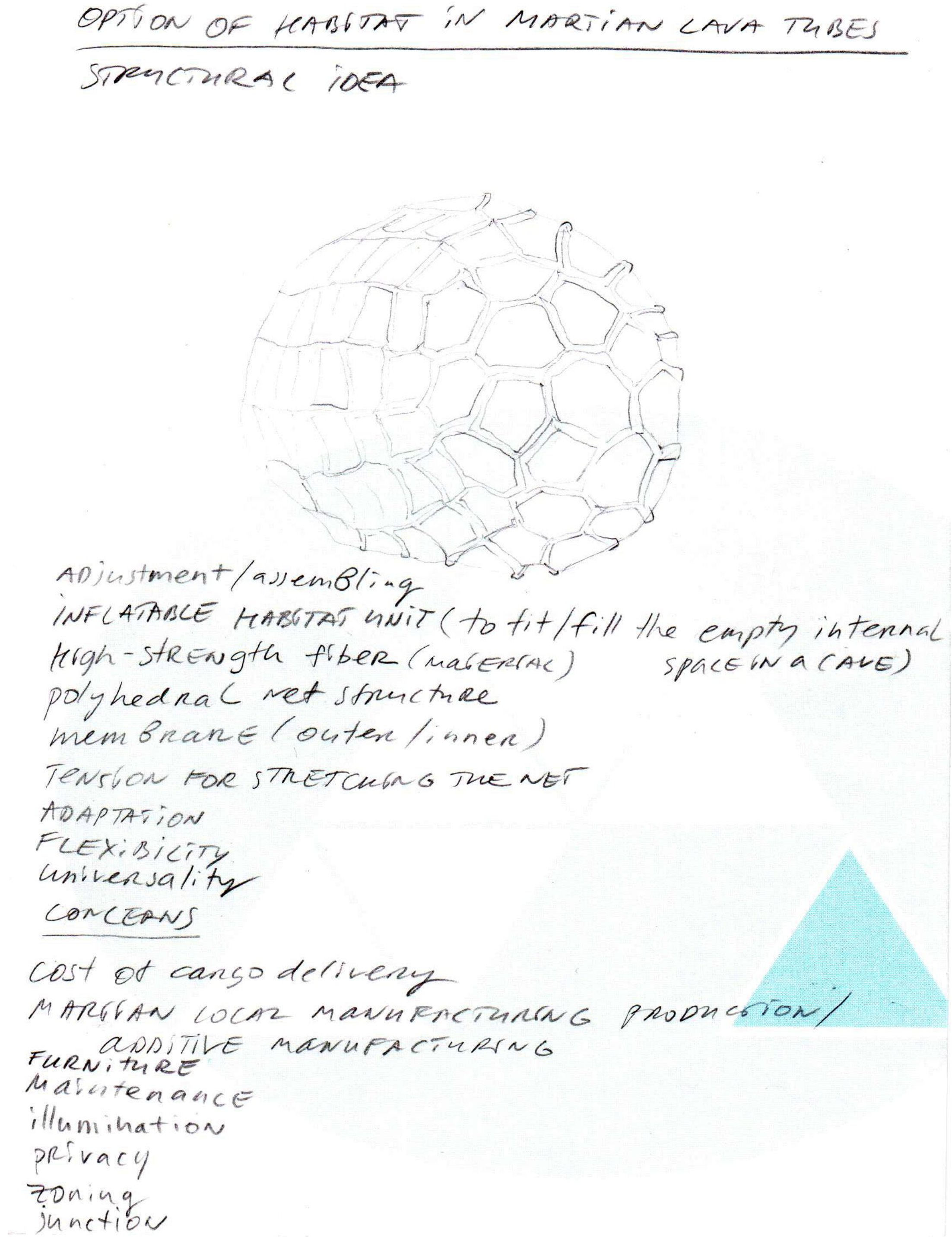
It is necessary to note that some of my ideas, which were created during the Creative Concept Generation phase, became the inspiration for my proposal of the final design of the food-growing unit.

In Innovative Conceptual Engineering Design (ICED) – Sustaining humans on Mars (2016, 23) there is a note about Biologically Inspired Design or BID. According to Yen (2011), BID relies on biomimicry or imitation of the principles of biological systems, methods and mechanisms created by nature. It is possible to note that aimed for innovative solutions, BID should inspire in solving engineering challenges. I was thinking that it might be metaphorical to design a plant-growing unit inspired by nature. Since among my teammates we were speaking about algae and a few times fungi, it was curious to Google some micrographs of insect eggs, plant cells, fungi, microbes. The searched results gave me some ideas for designing the shape and the structure of the growing unit. A moodboard and the sketches are provided in Appendix 2.

However, it is necessary to note that the facts on Mars and other knowledge I gained during the Team Learning and Knowledge capture affected my search process. As I learned, according to the project requirements, the food-growing unit should be easy-to-use, fast to assemble and disassemble as well as easy to relocate. Thus, while looking at the pictures of different cells I was simultaneously analyzing the structures in terms of reliability to my “arising” idea.

In addition, I was constantly keeping in my mind the thoughts of some of NASA’s experts about the usage of a lightweight inflatable structure for a Martian habitat (see 2.4.7 Project requirements).

As a result, I came up with the idea of a capsule shown in Picture 4. Although I was satisfied with the shape I found, at that time it seemed too conceptual to me. That is why I turned my attention to plant-growing chambers at the ISS and tried to apply their most sufficient elements to my design (Astronauts are growing lettuce, flowers in space 2016).



Picture 4. Sketch of capsule structure (by the author in 2016).

3.4 Plant-growing chamber

According to this proposal, the plant-growing unit should be represented by a convenience deployable system, a membrane and covered with a lid. The four holes in the lid were designed to allow the potatoes' roots protrude through (see Figure 11). Thus, the suspended roots should be hidden inside the chamber since root crops, the tubers, must require protection from light that may evoke the synthesis of chlorophyll. The greenery of potatoes must be outside of the chamber.

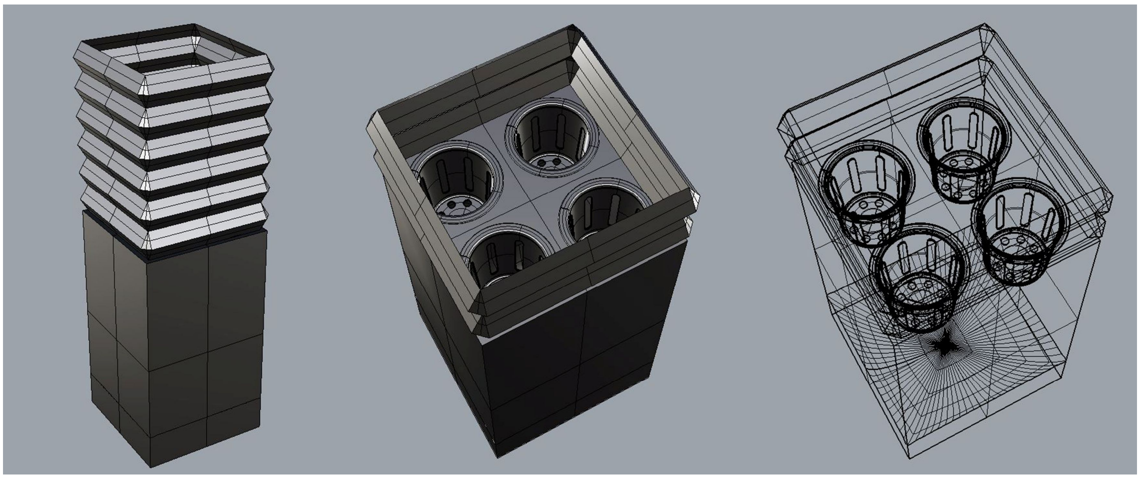


Figure 11. 3D model of the plant-growing chamber (Idea by BioMars team in 2016. 3D modelling by the author in 2016).

A small-sized and compact plant-growing chamber would be easily moved around and placed almost anywhere in a Martian greenhouse. An enclosure should create a shelter that would allow controlling the environment inside the chamber to set optimal parameters for the microclimate required for plants. Thus, the internal temperature and humidity as well as lighting could be controlled individually for each plant, independently from the surroundings. The transparent material of the enclosure should allow for the exposing of the plant and through that provide a sense of interaction with plant.

In addition, a monitoring system with an adjustable timer should allow monitoring and setting the necessary parameters needed for a particular plant. Moreover, it would inspect a plant's condition, collect all the data, analyze it and provide information about the conditions inside the chamber. The Monitoring system should report via a signal to a robotic automation system about the needs of water, heating or other demands. Additionally, it should inform users when a plant would be ready for harvesting. Robotic automation system, in turn, should be able to keep routine while the Martian settlers would be outside of the habitat for a while.

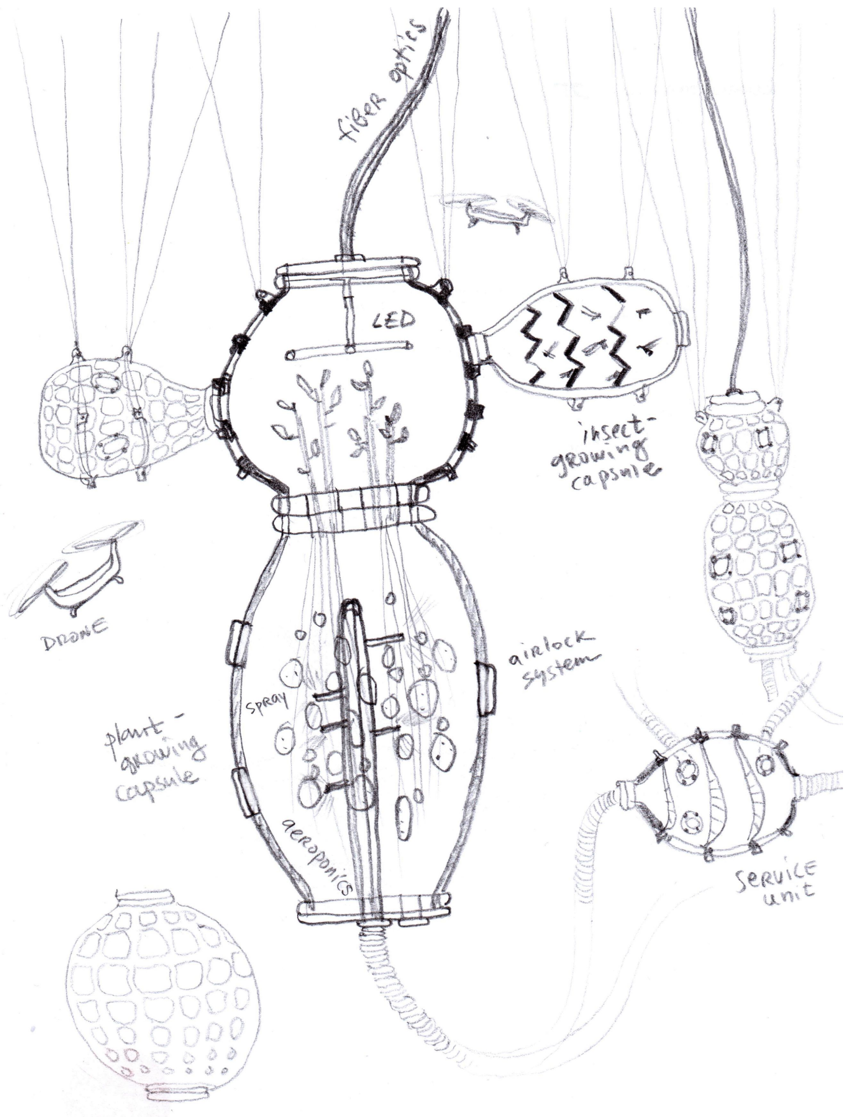
The plant-growing chamber would utilize an aeroponics system that should contain a misting system and a water reservoir at the bottom of the chamber. All the nutrients must be delivered for the plant root in water. Water must be recyclable: water from the water reservoir would be pumped up, dropped on to the roots and flow back down along them to be collected again in the reservoir. This must include not only the continuous recycling of water, but also that of the nutrients.

3.5 Epilogue

It was apparent that my thesis should aim to represent my personal perception of design for the concept of a food-growing unit. Looking at the renderings of the plant-growing chamber, I realized that I faced my own challenges as a designer and an architect: the design I was developing finally lost its uniqueness and features. It turned into a maybe useful and practical but regular object. In trying to come up with some “fresh” approach, I was reviewing my sketches done during concept ideation phase. Time passed, but I still saw the potential of my idea of an inflatable airtight capsule. I was thinking one should not mimic existing things. My design should not be recreating Earth-like scenery; my concern was Mars!

Having my doubts, I had to write the thesis. When working on the project requirements chapter, for some points I had to re-read Innovative Conceptual Engineering Design (ICED) – Sustaining humans on Mars (2016). Since my mind was busy with creativity, I discovered a new side of the ICED methodology, the creative side. I found the messages about “…the importance of novel ways of approaching problem solving which are creative…" as well as an idea of "…stretching the limits of our imagination…" (Innovative Conceptual Engineering Design 2016, 10, 12).

Those words enhanced my courage and gave a free hand to propose my idea to my teammates. During our regular workshop, I drew a sketched version of my proposal and explained its main aspects (see Picture 5). I would like to thank my team who supported my idea. My special thanks went to Timo Ilo, Master's Degree student in Biology at University of Eastern Finland (UEF), who suggested to consider drones to serve the food-growing system as well as to add the Service Unit (see 4.6 Service Unit).



Picture 5. Sketch of the concept (by the author in 2016).

4 FINAL DESIGN

Concept development and design proposal of the food-growing capsules on Mars are represented in Figure 12.

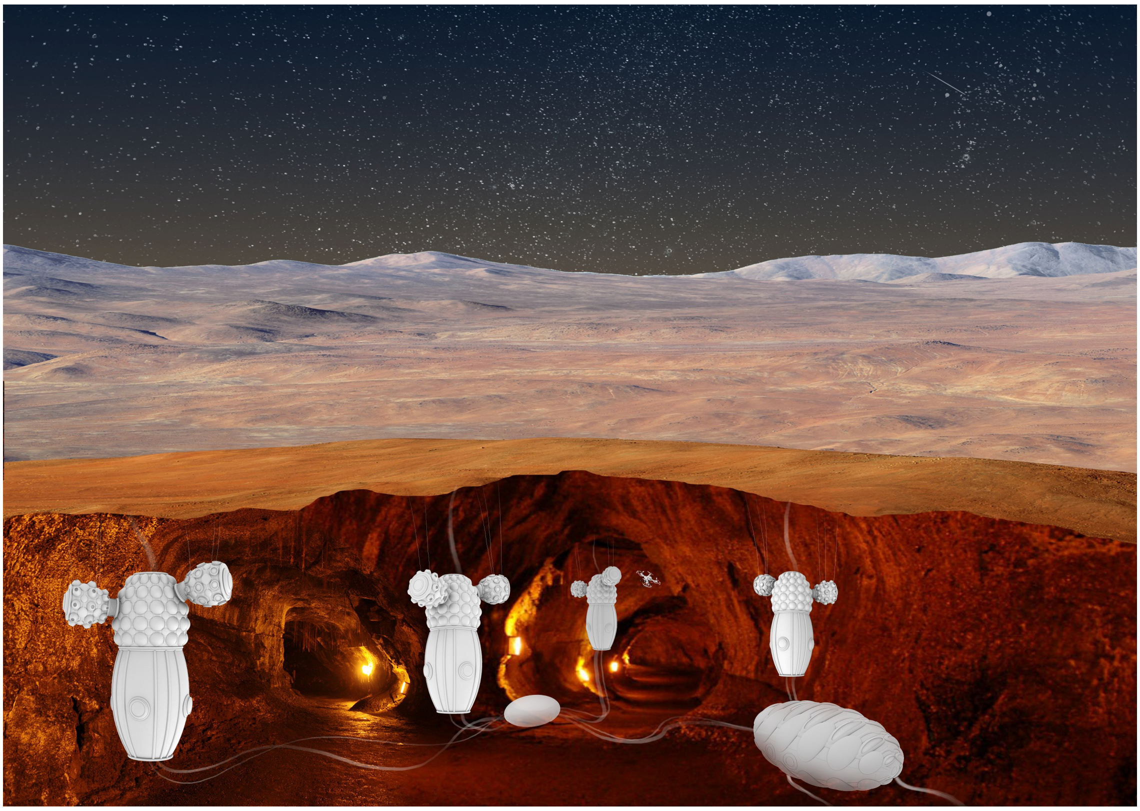


Figure 12. The food-growing capsules (by the author in 2016).

4.1 Concept

Regarding a sustainable approach, the food-growing unit should be developed as a self-sufficient system, which allows harvesting high-yield crops in a limited space. Planting, growing as well as harvesting processes should be automated, at least unless the first Martian occupants will come and later in case of their absence due to the exploration missions and other work purposes. An automated system would require the regulation of a microclimate inside a system, the control of air circulation and lighting, watering as well as nutrient delivering. In addition, the food-growing unit should rely on the recycling of natural resources. Besides, drones should be used as an advanced control system in order to perform routine duties taking the place of Martian settlers. Moreover, the drones should check on the food-growing unit and its condition. Furthermore, it would be crucial to consider the integration of the food-growing unit with life support system (LSS) in terms of the exchange of carbon dioxide and oxygen.

According to the concept, the food-growing system should be divided into several parts. Each part would represent an individual growing-unit for the separate growing of plants, insects and algae. The plant-growing section should be designed for the aeroponic gardening of potatoes. The other two units would house insects and algae. Each of the units should offer the required growing conditions.

In addition, an individual power-generating adapter should keep the food-growing system with power and provide electrical energy when it would be needed. In an emergency case, this adapter must be activated automatically to keep the general system working while troubleshooting. Hence, the adapter should be able to supply power for 12 hours. Furthermore, the food-growing unit should contain air purification and filtration as well as water and nutrient recycling systems. Excess oxygen produced by algae could be stored for human use. The food-growing system should have the required internal atmospheric pressure for habitats on Mars. The plant-growing unit should have an elevated carbon dioxide level, while the insect-growing section would require an oxygen supply.

4.2 Growing capsule. Shape, principles of structure and function

Ideation process and parametric design of the structure are represented in Appendix 3. According to the concept design, an inflated tensile membrane structure should be considered as the structure of the capsule's shell. A net made of system of pipes should be defined as the main element of the membrane structure. In order to inflate the capsule, one should pump air in a way that air must flow through inflatable pipes until net become steady. Thus, internal pressurized air should serve as the main support component of the structure. The internal pressure inside the pipes should be equal or exceed the external pressure. PBO-filled sheets (see 4.4 Materials) should represent the external layer of the capsule's shell. The internal layer of the shell of the plant-growing unit should be coated by light reflecting nanoparticles in order to enhance light diffusion. Air could be used to inflate the capsule. Restraining structural tubes should create a shape and serve as structural constraints.

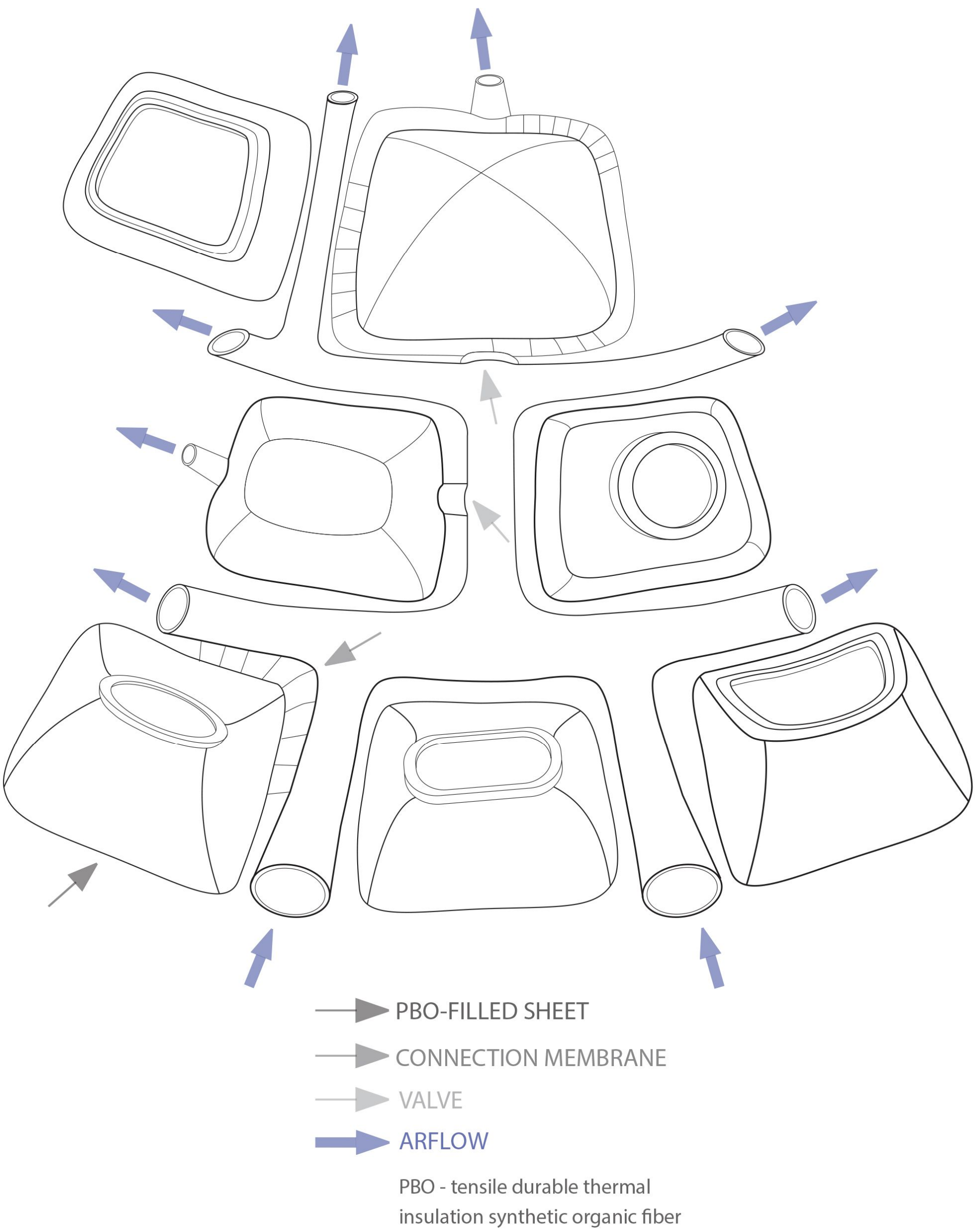


Figure 13. The principle of the structure. The proposals of the shape of the PBO-filled sheets (by the author in 2016).

4.3 Features of algae-, insect- and plant-growing capsules

Algae should be cultivated on Mars in a sealed capsule to avoid leakage. This closed system should prevent water evaporation and require the water circulation for aeration as well as for air exchange. An excess of oxygen, produced by algae, should be transported via an oxygen exhaust pipe to oxygen storage. The capsule must be designed with transparent inserting elements that should serve as skylights to provide light.

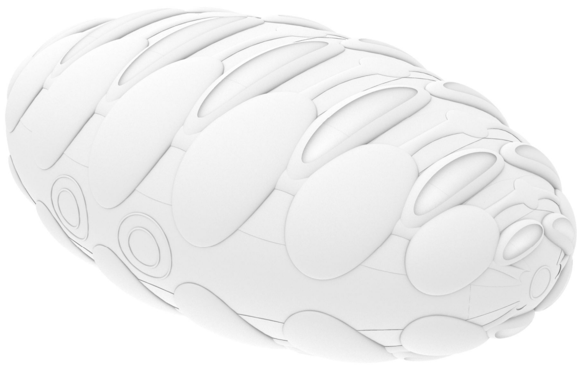


Figure 14. 3D model of the algae-growing capsule (by the author in 2016).

As with insect- and plant-growing systems, the enclosed capsule for algae should be controlled by a robotic automation system as well as a monitoring system and served by drones. It is necessary to note that an insect-growing capsule would be adjustable to the plant-growing capsules for air exchange. This should allow for the coupling of the capsules. In addition, the space tensile cables would fix and bear insect-growing capsules.

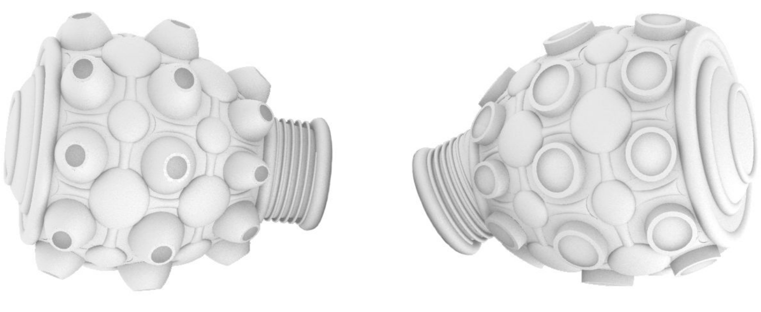


Figure 15. 3D models of the insect-growing capsules (by the author in 2016).

Although the shape of the plant-growing unit was modified, its functional features should be considered as it was explained in 3.4 Plant growing chamber.

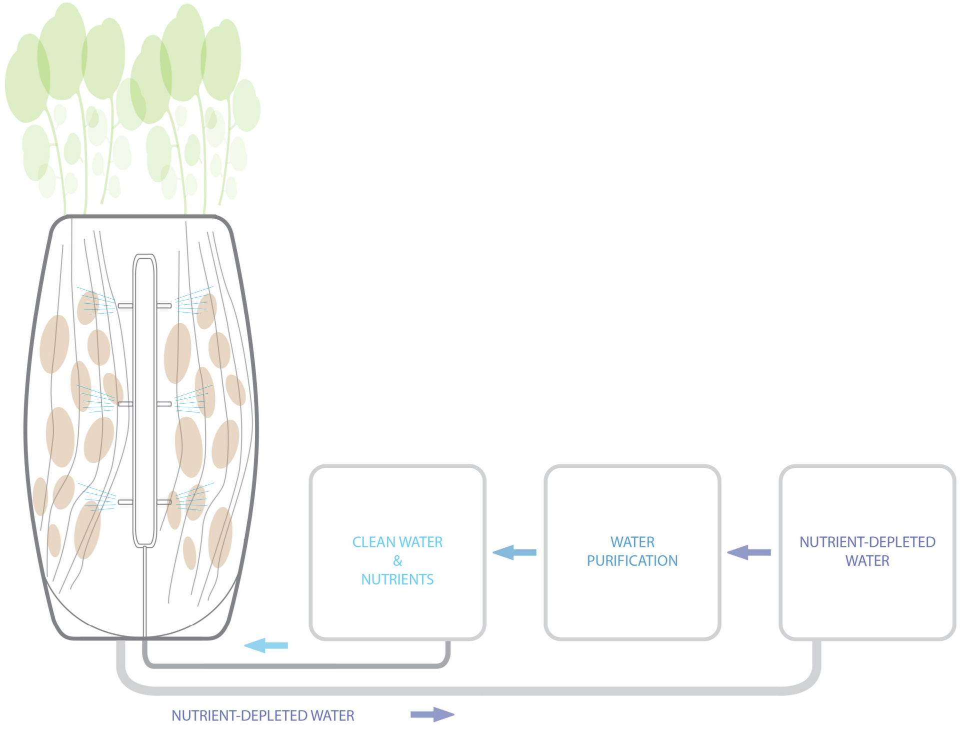


Figure 16. The principle of the aeroponic system for the plant-growing unit (Concept by Ilo in 2016; graphical illustration by the author in 2016).

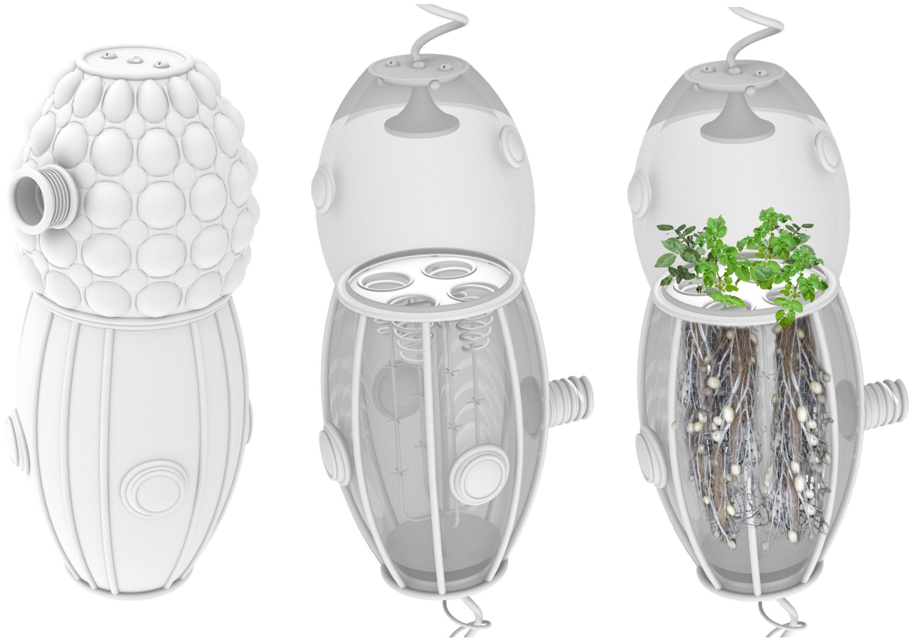


Figure 17. 3D models of the plant-growing unit (Concept and the principles of the food-growing system by BioMars team in 2016. Concept development, design idea and 3D modeling by the author in 2016).

4.4 Materials

The concept should be designed with the consideration of an air supported pneumatic structure with tensile fabric as a basic material such as the polymer Polybenzoxazole or PBO (Martin-Brennan & Wheeler 2000, 64-72). PBO is a synthetic organic fiber that is characterized by high tensile strength as well as good heat and flame resistance (Orndoff 1995, 1-2, 14). Thus, PBO is a durable thermal insulation material that is able to bear tension forces.

Due to the fact that capsules might have a comparably short lifespan, it is necessary to note that inflatable capsules could serve as temporary systems during the first years of Mars colonization and during Mars exploration missions. Hence, the inflatable capsules could be produced on Earth and taken as cargo to Mars. At the same time, according to sustainable approach and ISRU, food-growing units should be manufactured using enable resources on Mars. This would require additive manufacturing. Martian regolith could be used as a basis for local plastic and glass production (Bushnell & Moses 2015). Thus, the food-growing units could be printed in-situ by a 3D printer on Mars.

4.5 Control and service system

In order to sustain the life-support system on Mars, one should provide a reliable and durable operation system and its efficient management. All the systems must function autonomously. Moreover, the internal environmental control in each growing-unit should be automated.

It is necessary to note that the growing system needs the continuous operation of a ventilation fan in order to provide air recirculation as well as to maintain the pressure required for the capsule’s structure. That, in turn, would require an emergency power supply that could be provided by a power adapter (see 4.8 Hybrid lighting system). Each growing system should require an individual air exchange control and the monitoring of external and internal conditions of each capsule by a robotic automation system as well as a monitoring system.

Drones should perform not only insect and plant growth management but also the process of harvesting. Drones would take care of insect feeding and breeding as well as cleaning and maintenance the insect-growing capsules. Drones could check out, analyze and fix any detected damages of the structure of the capsules. This would allow Mars settlers to do their routine duties without taking care of food growing issues. At the same time, humans would be allowed to harvest non-crop species like spinach, lettuce and others if they would like to. Additionally, the service by drones should be a great solution for individuals who suffer from entomophobia.

4.6 Service unit

According to the concept idea, a service unit should be divided into the sections by the membranes. Each part should be designed for its own purpose. Division into parts would allow extracting some microelements and minerals such magnesium, iron and calcium (Ilo 2016). Additionally, it would allow preparing an output from bio-waste, a perfect filtered nutrient solution to be delivered by aeroponics to the potatoes' roots.

Insect scat is not only the unique source of fertilizer. Since e greenery of potatoes is mostly not suitable for insect diets, the uneatable parts of potatoes could be used for compost. This bio-waste should be conducted to a chemical reaction using a catalyst in order to convert compost into a dissolved substance. This would be necessary to prevent the precipitation of nutrients. It should not allow the nutrients to stick in the pipes and mist nozzles. Otherwise, this may cause a blockage of the whole aeroponics system. In addition, the misters must rotate and spray with a high frequency escaping the precipitation of undissolved elements in case of such an occurrence.

4.7 Airlock system

The equilibrium of the complete food-growing system should be well-established and robust. All the capsules must have the openings serving based on an airlock operating principle to minimize internal air leakage of each growing-unit while it is accessed. Thus, the capsule equipped with these integrated airlock-based openings should allow drones access to insects and plants while keeping the internal microclimates of the each growing system stable.

4.8 Hybrid lighting system

To match the sustainable approach and project requirements, energy efficiency should be of primary importance. Besides heating that would require a great energy demands, the concept should be designed with the consideration of a minimum loss of energy for lighting. That is why an implementation of the hybrid lighting system based on the usage of fiber optics as well as solar panels and light-emitting diode (LEDs) should be an efficient type of alternative and renewable energy.

The hybrid lighting system should rely on the conversion of sunlight in to solar energy by solar panels. The energy produced by solar panels should be used to power individual energy supply adapters as well as artificial lighting such as LEDs. Excess energy should be stored in batteries.

In order to keep the growing system self-sustainable, the implementation of optical fiber would be useful in terms of energy saving. Optical fibers should be integrated into an internal artificial lighting system of the underground greenhouse. Fiber optics should be able to guide natural full-spectrum sunlight to plants. Due to its flexible structure, optical fiber should provide sunlight over long distances into hard-to-reach places. It is necessary to note that optical fibers should be able to transmit the light efficiently; only minor losses can occur. This was proved while the BioMars team members (Ana Gebejes, Kristina Soloveva, Sonja Kuokka and I) were conducting the simple experiments on fiber optics in a laboratory at Joensuu Science Park in 2016.

The concept of the food-growing unit could be developed while taking into account the implementation of a hybrid lighting system. The hybrid lighting system should consider ISRU in terms of robustness and in-situ excitability. According to my idea, the design proposal of the hybrid lighting system should contain four elements such solar panels, parabolic mirrors, optical fibers and light emitting diodes. The system should rely on the principles to be explained.

Sunlight should be collected with a system of parabolic mirrors to be captured and transmitted into a plant-growing unit by fiber optics. In order to collect sunlight, the system of parabolic mirrors should be installed outside the underground greenhouse on the Martian surface. The first parabolic mirror (collector) would create a maximum accumulation of energy at a focal point, the point where all reflected rays of sunbeams should intersect. To prevent overheating and further melting of the edges of optical fibers, it would be necessary to use a second parabolic mirror as a concentrator of energy that should reflect the light from the focal point to be captured by optical fibers (see Figure 18).

According to the design idea, the system of parabolic mirrors should be enclosed by the solar panels. It should provide artificial lighting by LEDs when using natural light is not possible. Solar panels should be designed following the principle of flower structure (see Figures 5, 6 & 7 in Appendix 1). The solar panels' folding structure should mimic the principle of a flower shape: its deployable mechanism should allow for unfolding and folding of the "petals", placed around the system of parabolic mirrors. Thus, the structure should serve as a shield being folded at nights as well as during Martian dust storms, protecting the external part of the hybrid lighting system from dirt and extremely cold temperatures.

It is recommended to keep a required fixed distance between plants and LEDs. The position of LEDs would adapt to the plant height. The flexible position of LEDs would keep the required distance, and this should be better for plant growth rate than the varying distance. The optimum fixed distance, which should be controlled by a robotic automation system, might affect the growth of a plant positively by eliminating the harmful factors of hot and dry air produced by LEDs. Consequently, that would prevent the drying of a plant.

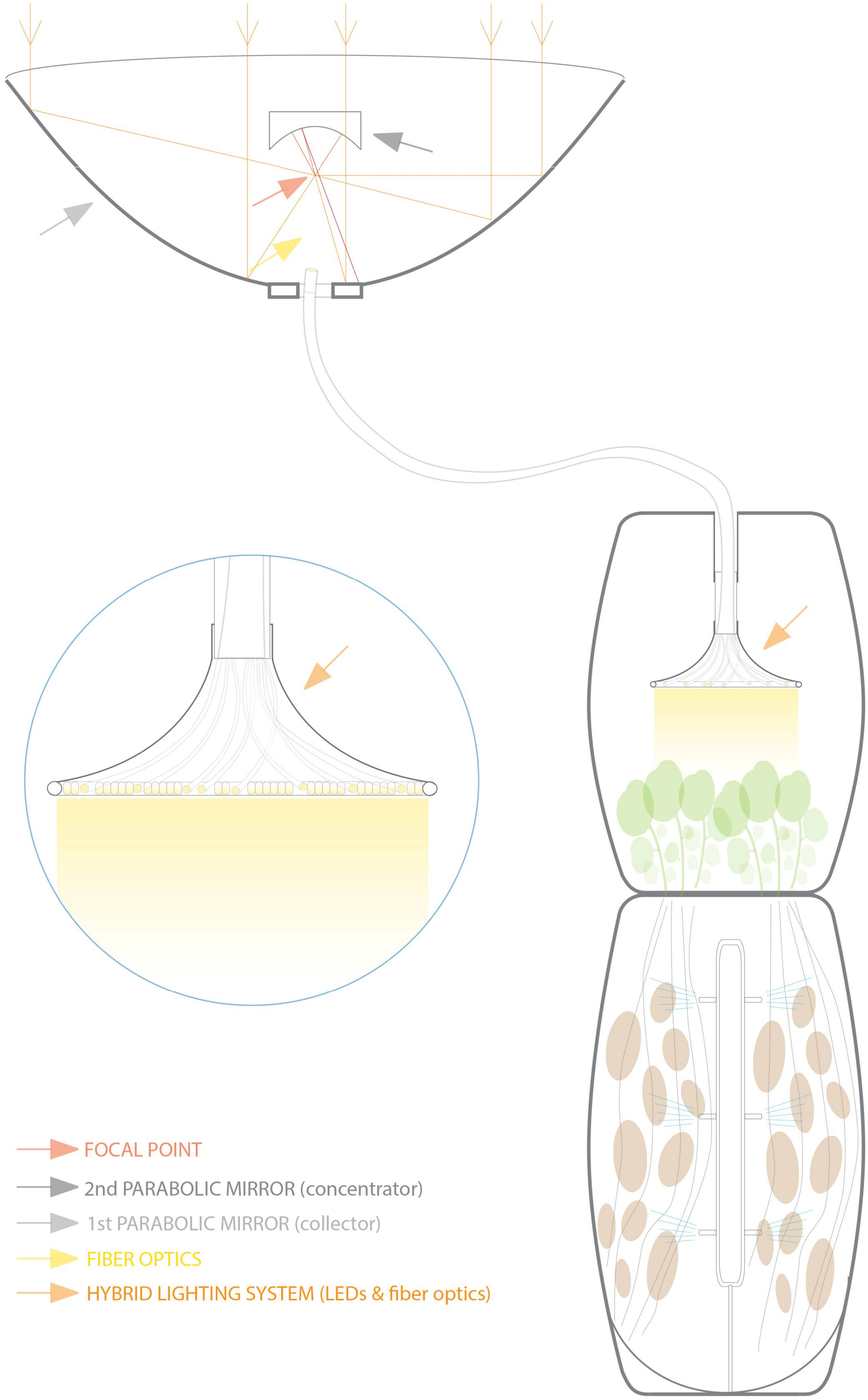


Figure 18. The hybrid lighting system (Concept development by Soloveva & Smirnova in 2016; consulted by Gebejes, Ibrahim & Karhu in 2016; design idea and graphical illustration by the author in 2016).

4.9 Features of the concept

In order to define the concept and its function the System Architecture should be used. This advanced creative and innovative tool should be able to represent a working principle of the food-growing system developed by BioMars team (see Appendix 4). According to Do (2012), System Architecture relies on a system of components and the interactions between them. This should aim to distinguish the concept's features.

What would be the singularity of the current concept proposal? What would be the features, which distinguish the present food-growing system from other Mars related design projects?

As explained in Existing Solution chapter, during recent years some international projects have been working on the similar challenges as the one of me and my teammates. At the same time, one should admit that comparing with, for instance, the similar Moon Palace-1 the present concept would assume some added benefits. In order to demonstrate the advantages of our food-growing system, a simple comparison should be made.

- Robustness and redundancy

The food-growing system developed by BioMars team should get a priority regarding robustness and redundancy in terms of some spare parts for the growing units. The represented design should be developed as a set of individual and self-sustaining food-growing units, while Moon Palace-1 should rely on the regular structure of a greenhouse: a plant cultivation module filled with normally growing plants. Thus, in case of damage caused by, for instance, meteor attack, all plants in Moon Palace-1 would be lost, while the separate self-efficient food-growing systems with an individual power supply adapters would withdraw.

- Sustainability

The food-growing system is sustainable. Its design could be applicable for in-situ production using local Martian materials. Moreover, the concept should consider the recyclability of materials used for our design. It should allow multiple uses.

- Flexibility and comprehensiveness

The food-growing system is defined as flexible and universally applicable. Its system would allow growing different plants simultaneously, which require different growing conditions.

- Advanced hybrid lighting system

The present concept should provide not only LED lights, but also natural sunlight due to the hybrid system of lighting. Moon Palace-1 was designed considering artificial lighting only.

- Aeroponics

As it was explained earlier, our concept should be intended to be used for aeroponics instead of soil that was chosen for Moon Palace-1.

- Advanced automatic control and service system

In addition to the automatic system, the drones should serve for supplementary control and maintenance as well as for feeding of insects and crop harvesting, collection the scat and its further delivering to Service unit (see 4.6 Service unit). Generally, Mars habitant intervention should not be needed, unless they would like to interact with plants.

4.10 Epilogue

The inflatable capsules should be useful for the food-growing system prior the Mars colonizers' arrival. Looking further, these capsules should still be sufficient while the settlers would be outside their habitat exploring Mars.

I would like to cite the perfect words by Theodore von Karman: "Scientists discover the world that exists; engineers create the world that never was" (Theodore von Karman cited in Innovative Conceptual Engineering Design 2016, 15). However, being a non-engineer, together with BioMars team I tried to create the world that would be.

5 CONCLUSION

Sustaining humans on Mars was the challenge that the concept proposal of the current thesis should solve. The goal was to develop a food-growing unit, which should be appropriate for Martian habitat and meet design requirements for the extreme environment of the Red Planet.

In the present thesis the sustainable approach was considered regarding the economic, environmental and social features. In addition to sustainability, the crucial features of the design should be robustness, redundancy and user oriented design proposal for the final concept.

As a primary concern, in order to sustain people on Mars, it was important to consider human needs. The food-growing unit should aim to meet the demands of the Martian inhabitants. The need of high protein and nutrient dense food, oxygen and clear water were defined as vital.

The holistic approach of the concept proposal should be estimated as one of the main advantages. The aeroponic system and selected bio-elements such as potatoes, insects and algae were assumed to be a reliable proposal for a self-sufficient ecosystem on Mars. The developed system should be able to function beyond Earth.

Furthermore, one should understand not only human needs on the Red Planet, but also on the Martian environment. This implies the consideration of protection against the harmful effects of galactic cosmic rays and extreme cold as well as against micrometeorites and dust storms.

An underground location for the food-growing units was estimated as reliable. The inflated tensile membrane structure was considered as the suitable structure of the growing units. The lightweight capsule made of the durable thermal insulation synthetic organic fiber was proposed as a favorable solution for design of the growing units.

According to the ICED methodology, the food-growing system should be robust, easy to maintain, and enable in-situ production on Mars. In order to sustain and enhance the food-growing system, the concept proposal was developed as a set of individual small-scale units. The units should be able to provide different growing conditions depending on organisms. To keep the system operationally reliable, an advanced automatic control and service system was proposed. Moreover, it should allow Mars settlers to make their daily routine efficient.

In order to design a self-sufficient food-growing system one should consider not only an implementation of passive and active design strategies, but also the limits and constrains which the Martian environment should provide. Consequently, issues such as water and electric energy consumption were assumed as crucial. Thus, in order to sustain the food-growing unit efficiently, an advanced hybrid lighting system with an implementation of a renewable energy source and water recycling were regarded. It was estimated that the usage of alternative energy sources would make the project economically reasonable.

As a result, the food-growing unit was designed with an integrated approach, taking into consideration the ICED methodology and project framework, gained knowledge about space-related challenges as well as an inspection of similar problems and existing solutions.

In addition, it is possible to note that both subjects, Mars exploration and sustainable approach, should be considered as "the development that meets the needs of the present without compromising the ability of future generations to meet their need" (Lauring 2015).

6 REFLECTION

This thesis contains the information that was found regarding the mentioned topics in the Literature Review. Since at the time of writing this thesis the working process on the full prototype of the final concept is still in progress, there might be a need for future research, development and improvement. The possible cases of probable researches as well as possible development are noted below.

Although the results can be estimated as satisfied, there is still a room for improvement. It would be essential to consider an implementation of the smart self-healing materials and structures that should be able to define, analyze and maintain structural damage and failures. In addition, it would be sufficient to develop a regenerative ecosystem that could perform autonomously.

The thesis draws on the ICED methodology, facts on Mars and researches and shows my vision of space-related design through representing of the concept of a food-growing unit. In my opinion, the result is satisfying; however, some aspects could be developed. Initially 3D printing of the final full prototype was in the sphere of my interests, and it would be essential to accomplish this goal. Furthermore, as an architect I have an ambition to develop a parametric model of the full prototype in order to analyze its structure for optimization. Additionally, it would be advantageous to calculate the carbon footprint.

As was mentioned earlier, the thesis relies on the ICED methodology that includes concept development and experimentation taken into account of the feedback and recommendations from the experts. Thus, an area for future research draws upon a matter of conducting experiments on the final concept of the full prototype and its results. Depending on chosen idea for the final concept, there might be some specific features to be taken into account. Moreover, some solutions would require an additional research and consideration of scientific investigations.

In addition, it is necessary to note that although there is a lack of academic text in my thesis, there should be a possibility to enhance its content in terms of the reliability of sources. I have the ambition to develop my thesis project further. Thus, PhD work based on sustainability in the field of space-related architecture could be one of the options I am interested in. I would like to study a sustainable approach regarding the colonization of Mars from a holistic point of view.

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Figures appearing in the text

Each of the team members was able to propose at least ten ideas… (see Figures 1 – 4 in Appendix 1).

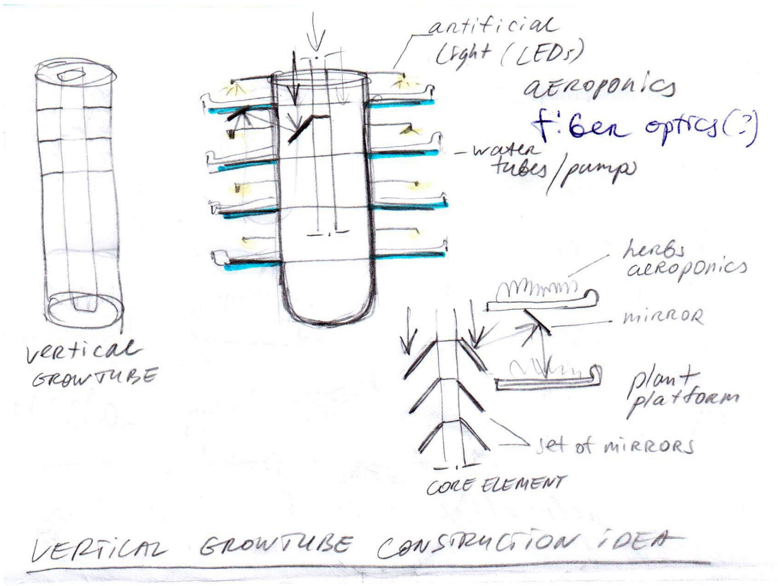


Figure 1. Sketch of an alternative version of the vertical Growtube.

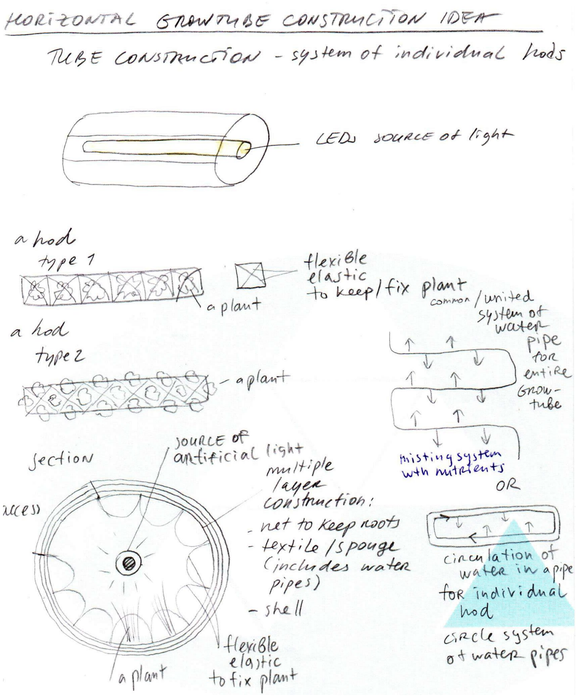


Figure 2. Sketch of the horizontal Growtube.

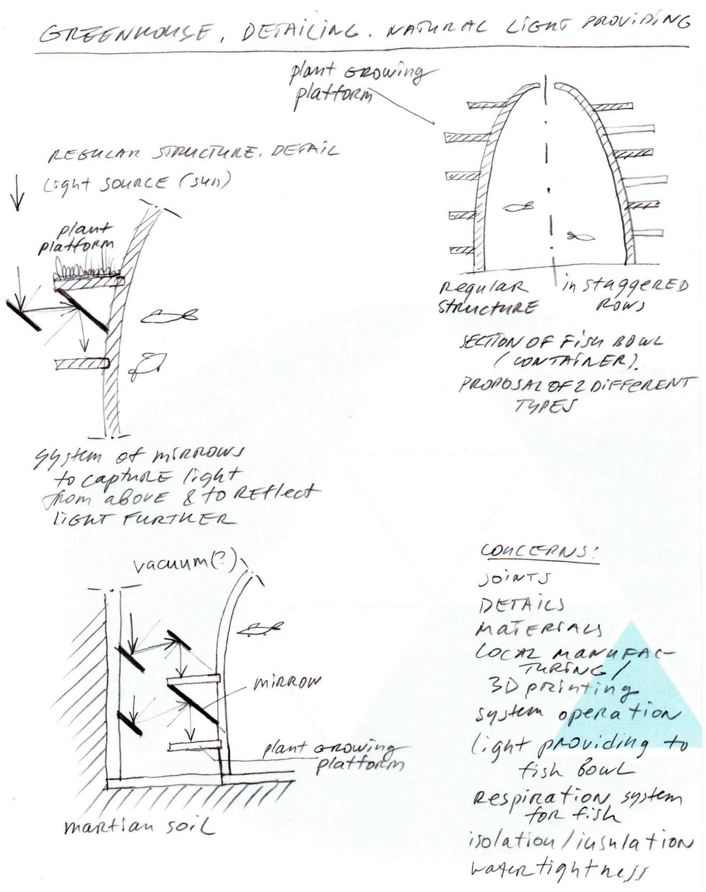


Figure 3. Sketch of a food-growing system.

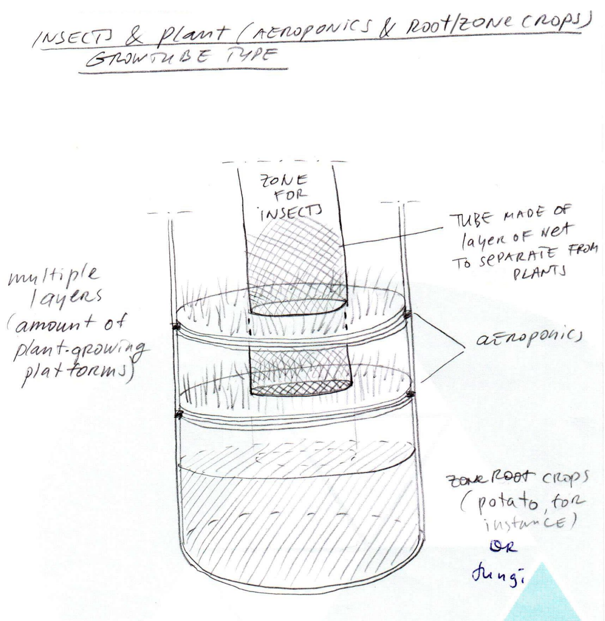


Figure 4. Sketch of a food-growing system.

Solar panels should be designed… (see Figures 5, 6 & 7 in Appendix 1).

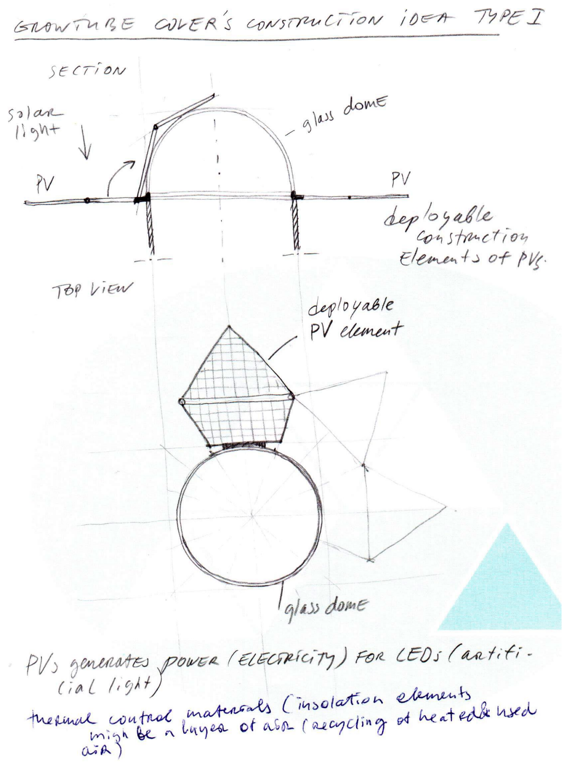


Figure 5. Sketch of solar panel system.

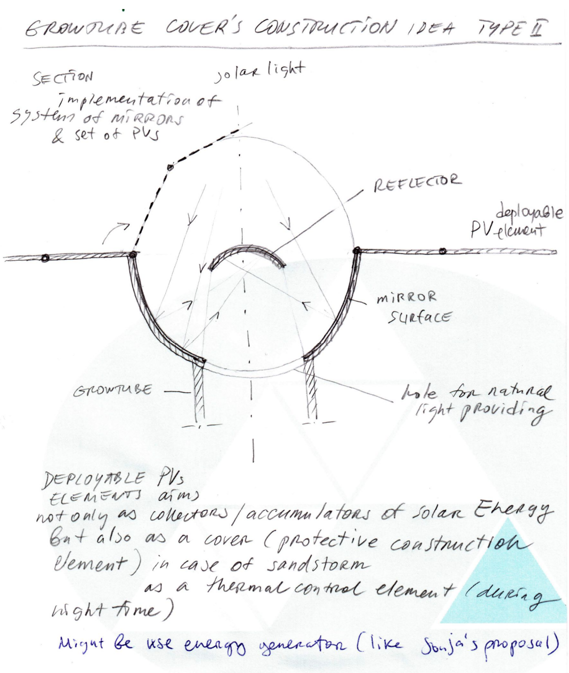


Figure 6. Sketch of the system of parabolic mirrors.

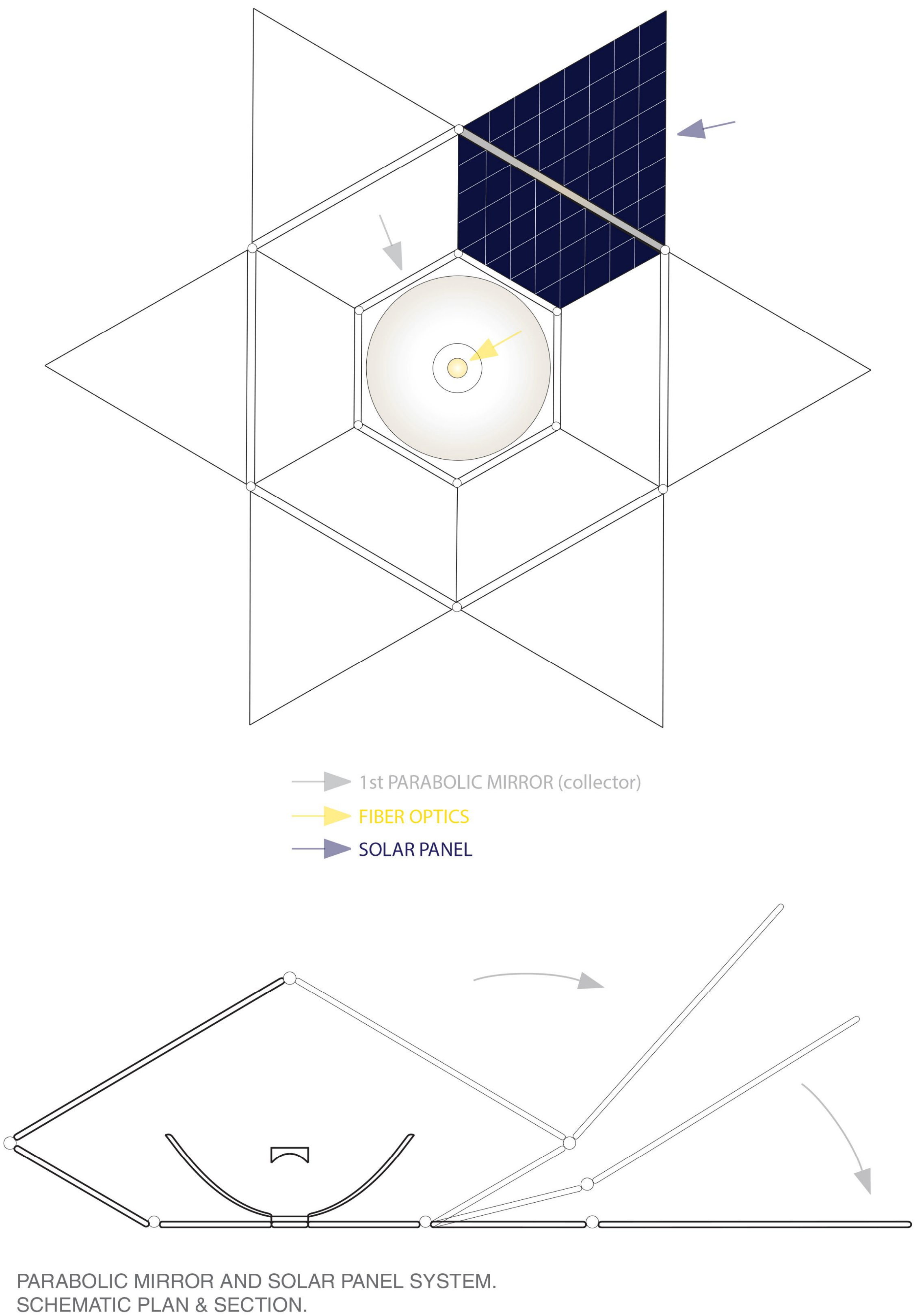
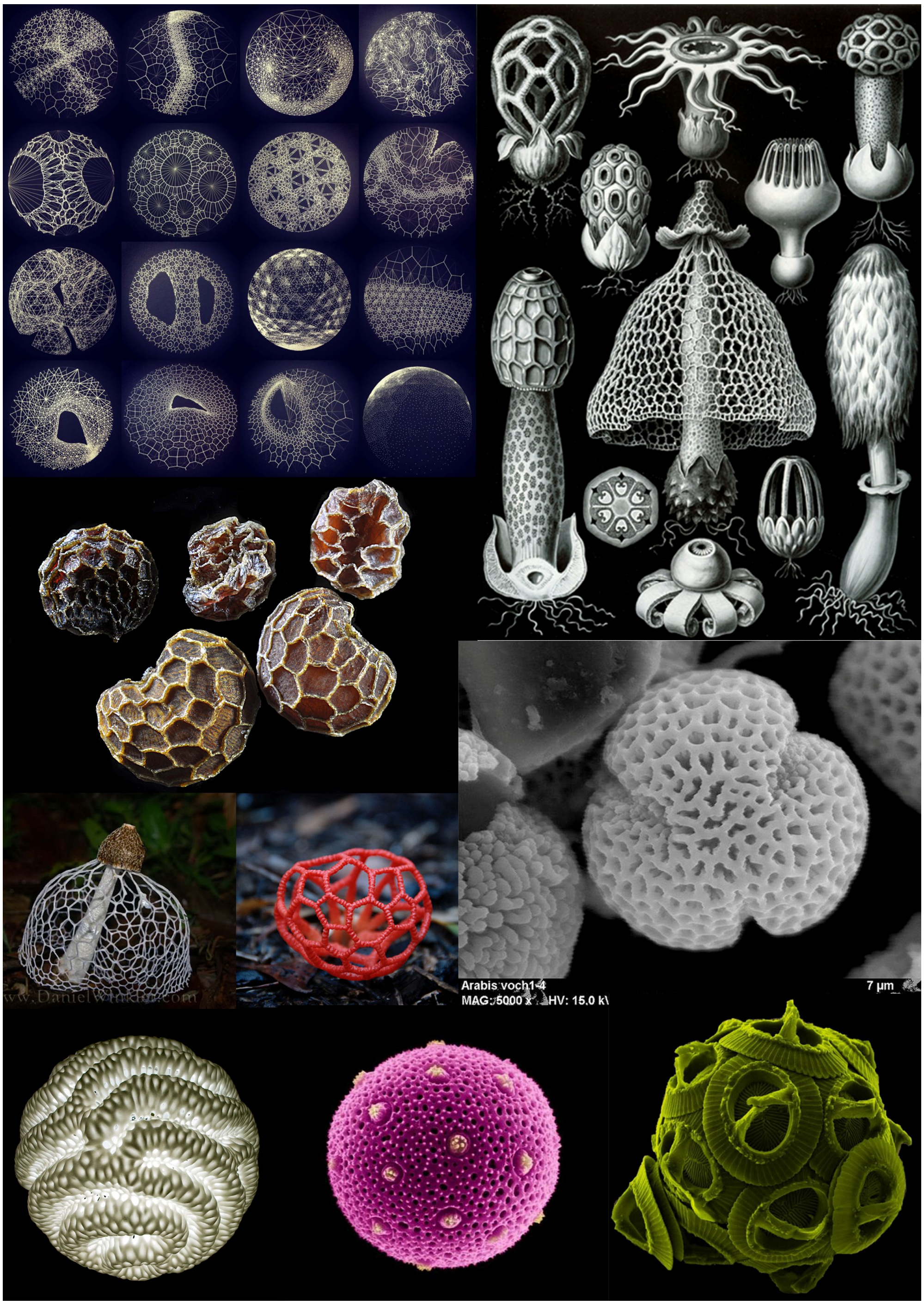


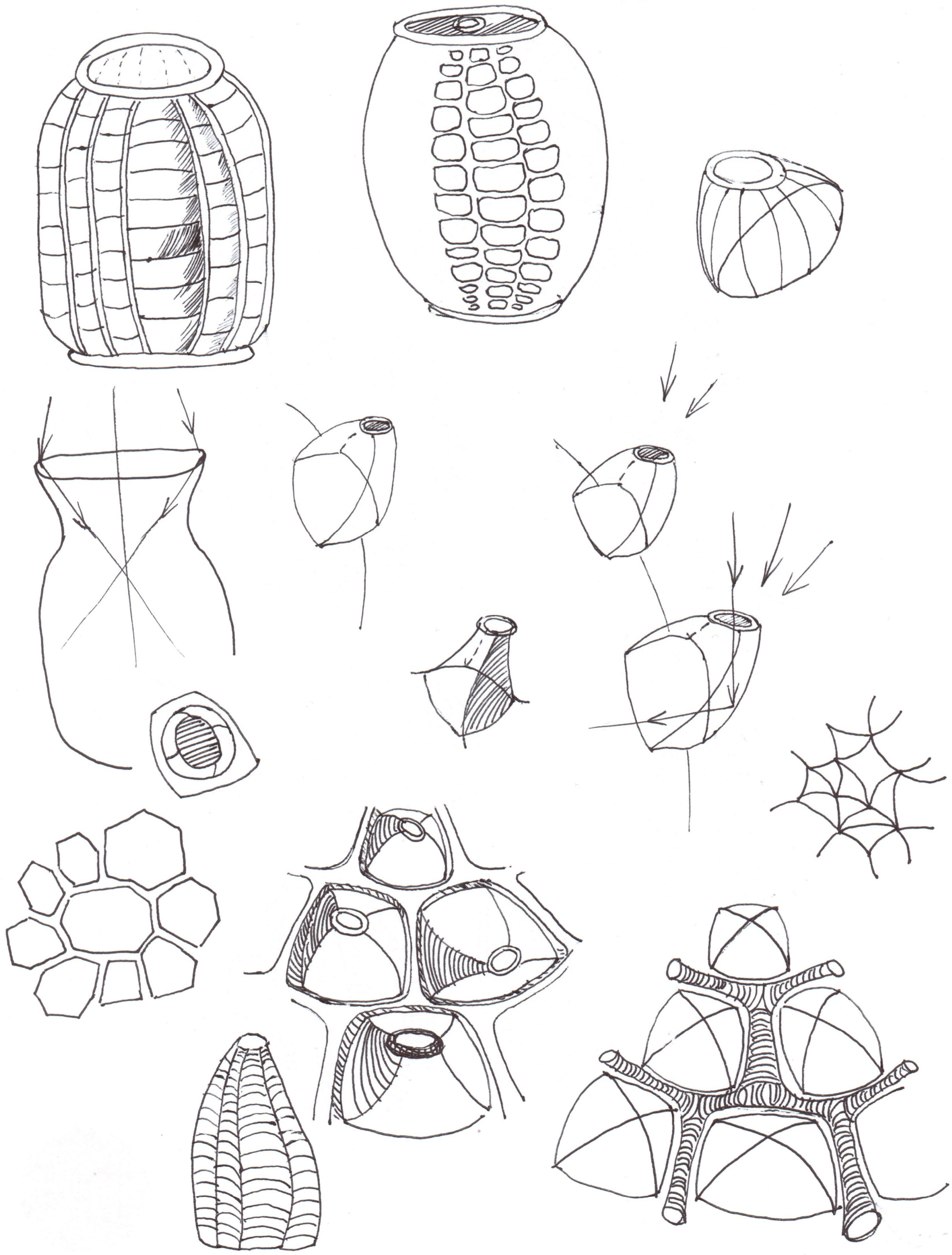
Figure 7. Parabolic mirror and solar panel system.

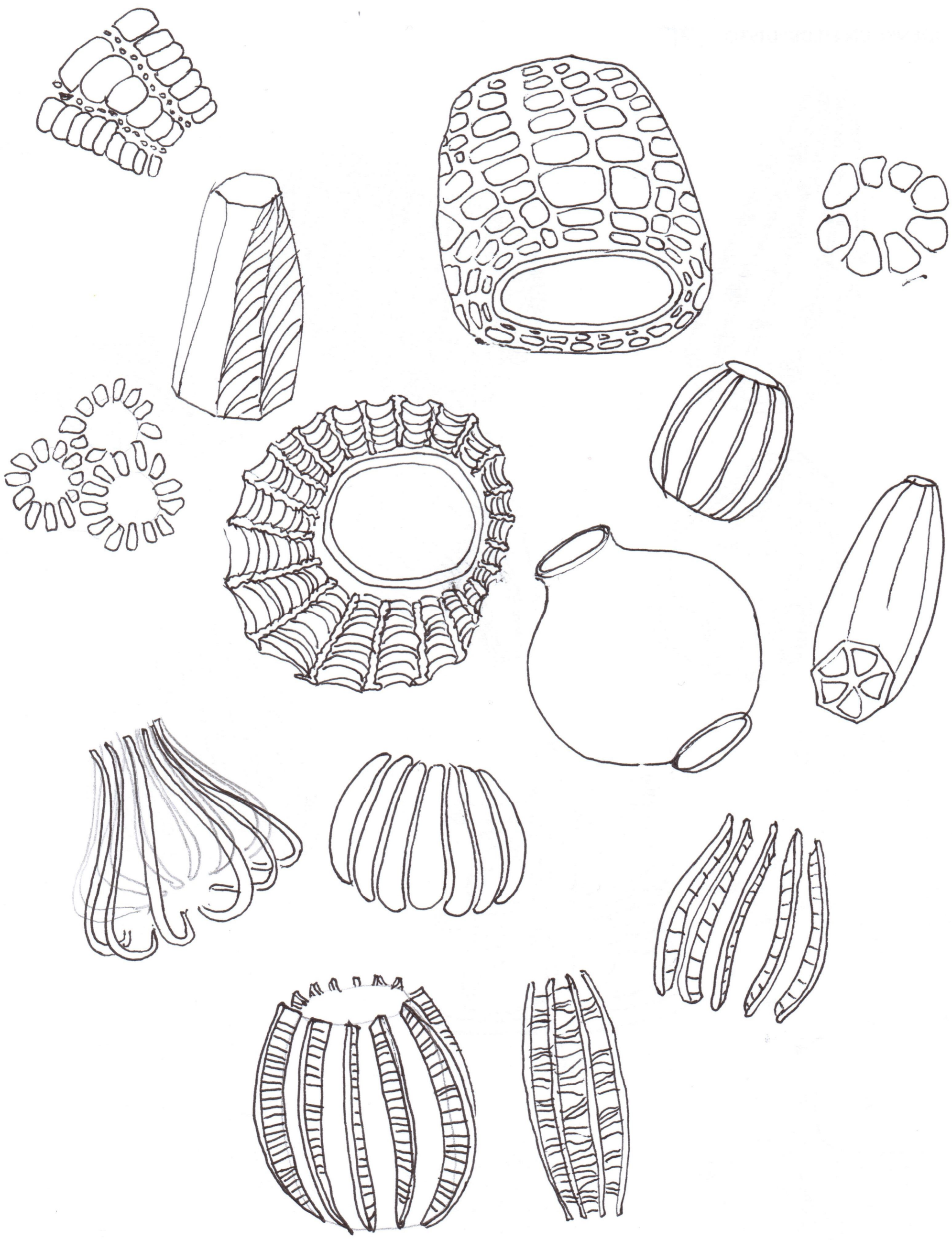
Moodboard and sketches

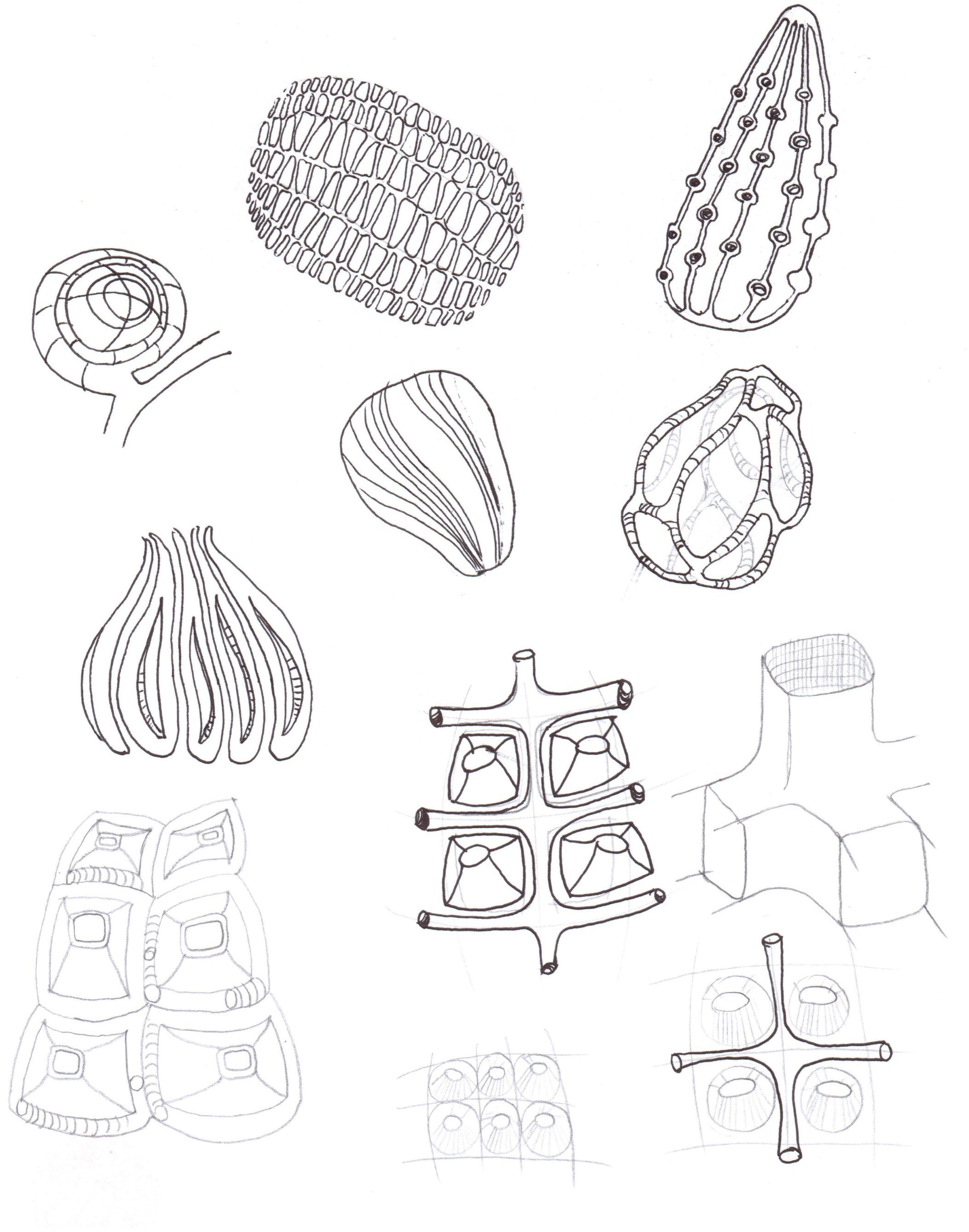
A moodboard and the sketches are provided in Appendix 2.

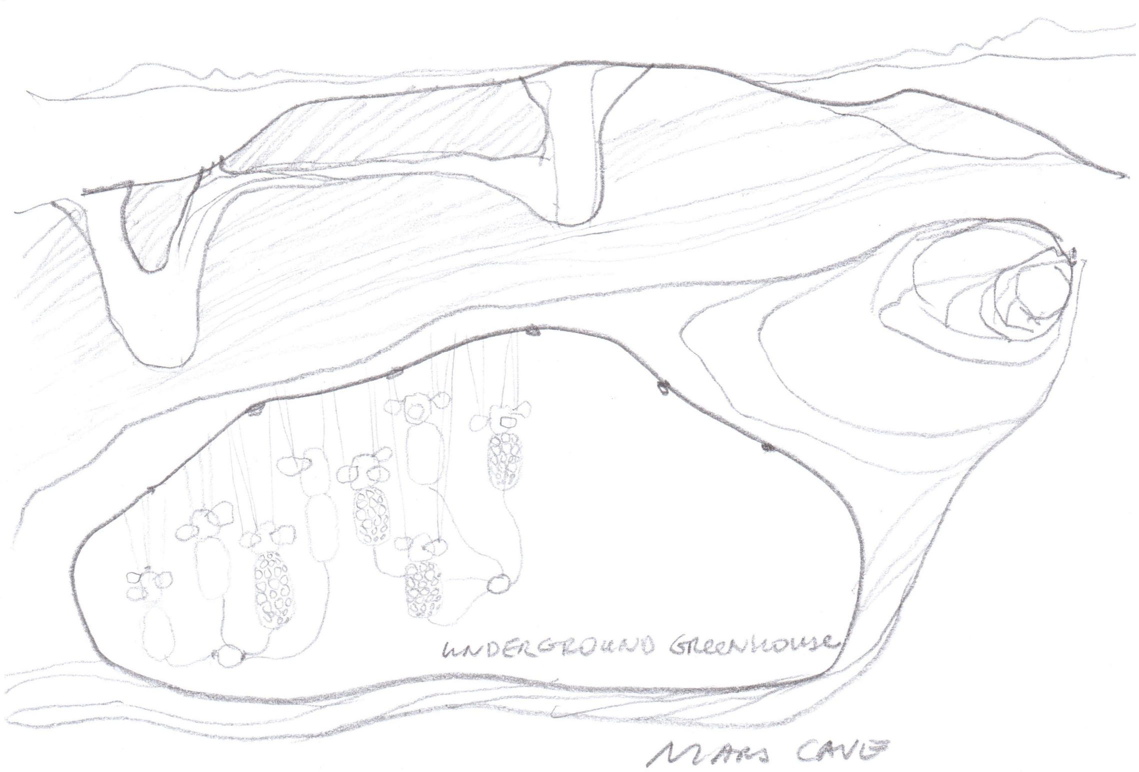


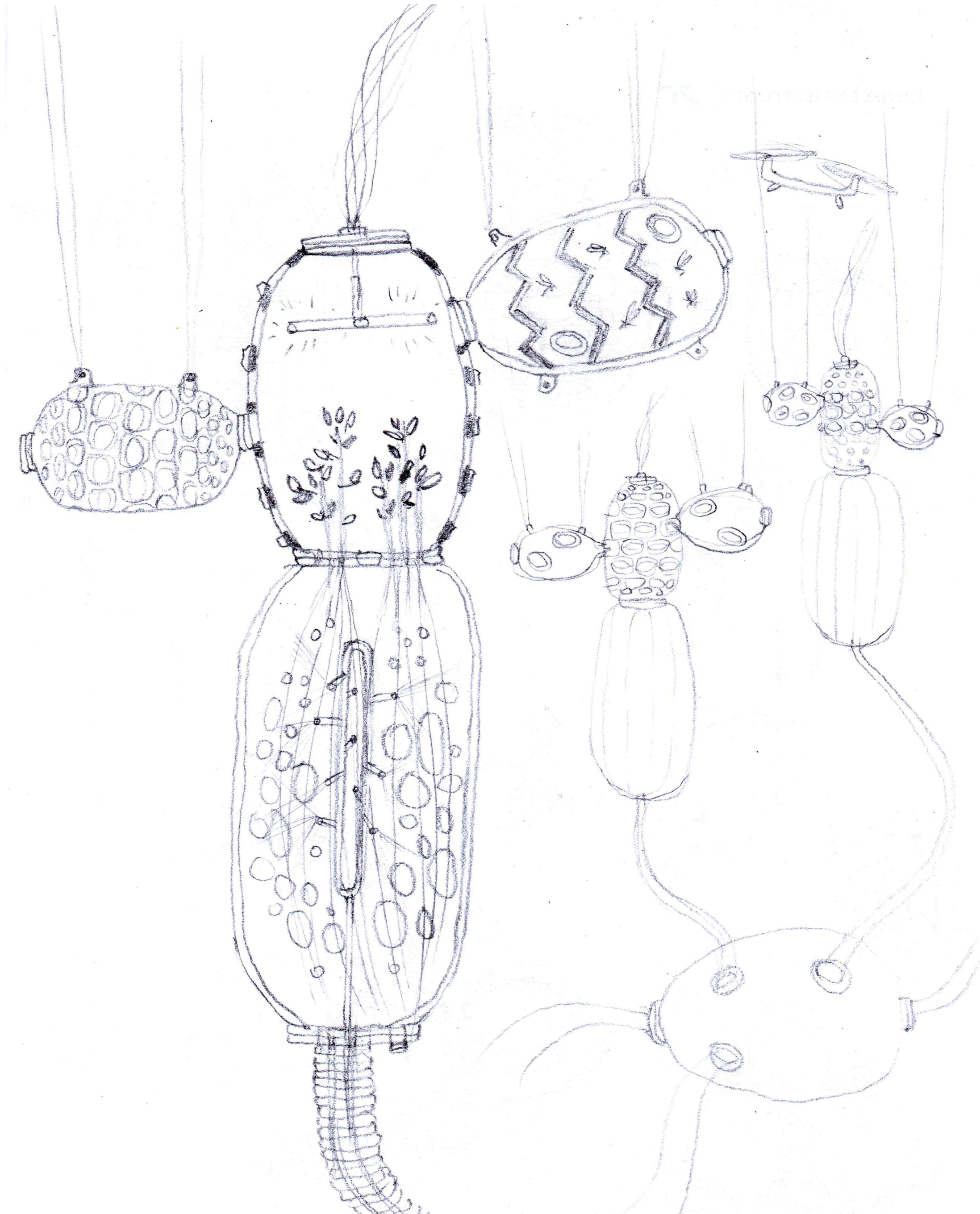
See the sources for the pictures used in the moodboard in Illustration sources.





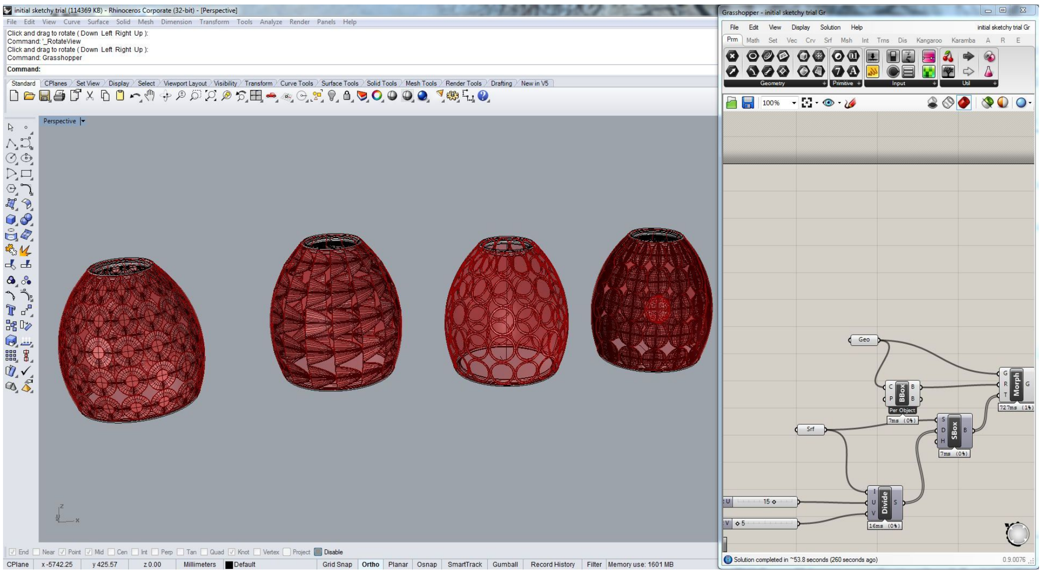


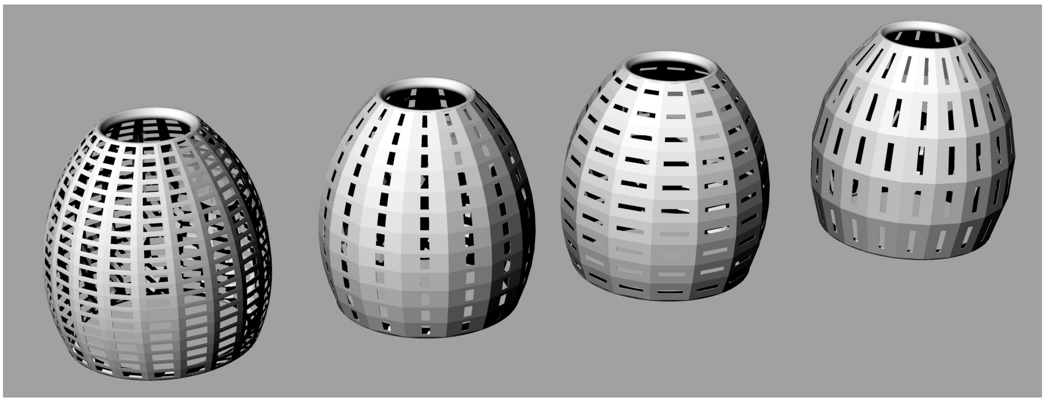

UNDERGROUND GREENHOUSE
MARS CAVE

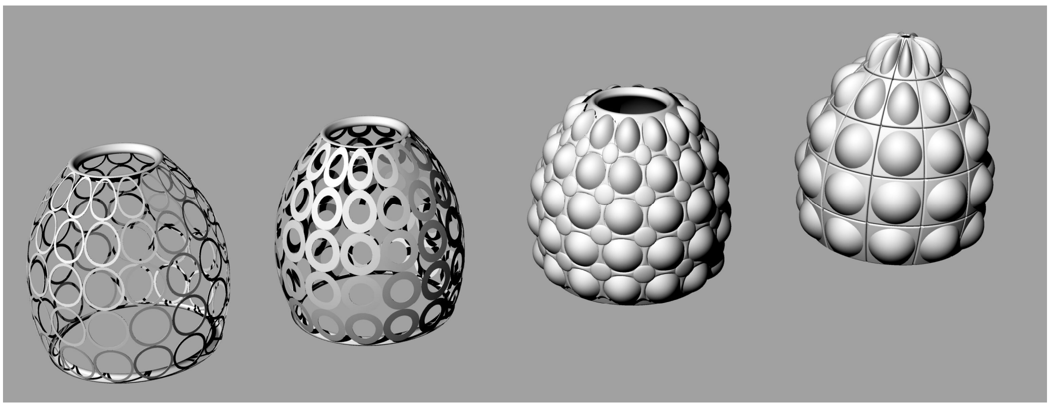


Parametric design. Ideation process and structure development

Ideation process and parametric design of the structure are represented in Appendix 3.

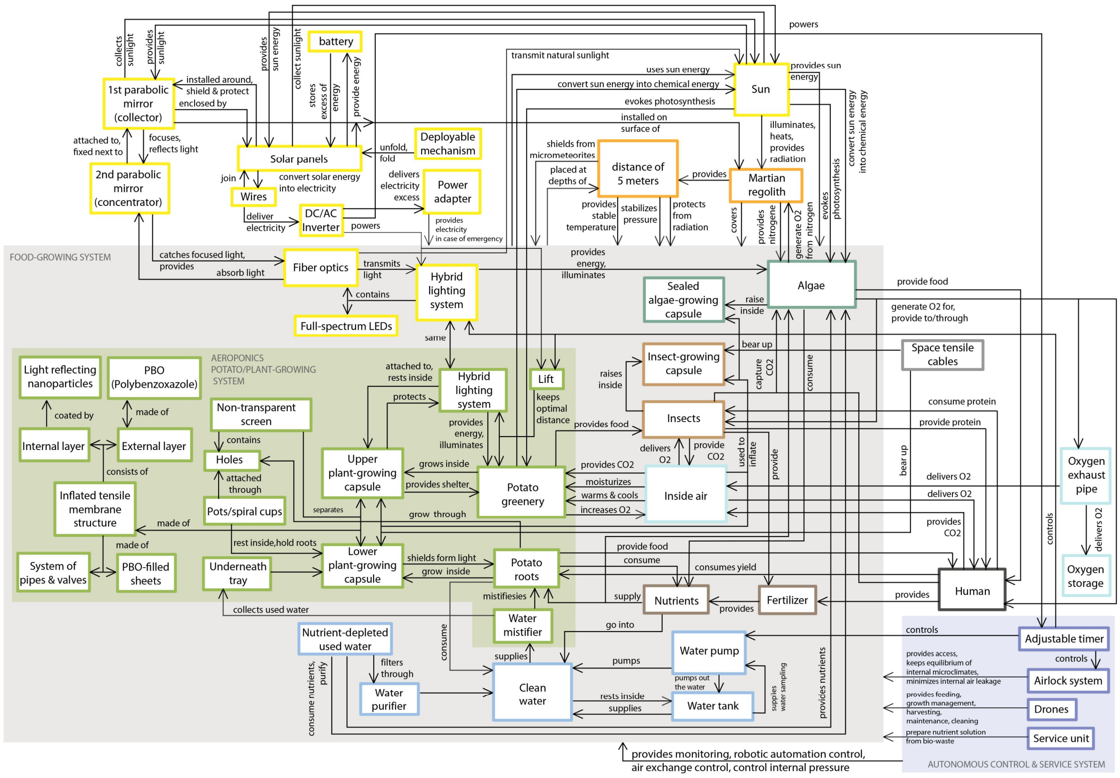






System Architecture of the food-growing system on Mars

System Architecture, advanced creative and innovative tool… (see Appendix 4).



System Architecture of the food-growing system on Mars (developed by the author in 2016 according to the personal design proposal and the ideas by BioMars team in 2015-2016).