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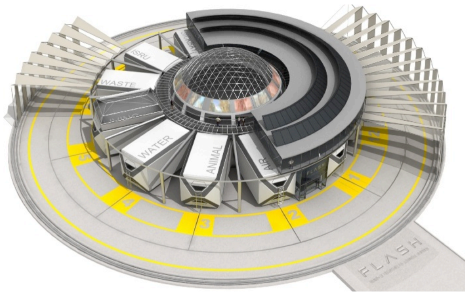

Study of the European Research Opportunity for the Facility of Laboratories for Sustainable Habitation (FLaSH)

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Thesis to obtain the Master of Science Degree in

Aerospace Engineering

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Abstract

This thesis aims to study the European research opportunity of the Deutsches Zentrum für Luft und Raumfahrt's (DLR) Facility of Laboratories for Sustainable Habitation (FLaSH) project. FLaSH's main goal is to research, develop and test Life Support Systems (LSS) technologies for materially closed-loop environments, for space and terrestrial application. The core element of the FLaSH is the Habitation Module Complex (HMC), which integrates 12 interconnected modules, each one of them addressing a LSS's domain in order to achieve a self-reliant habitat: *Air, Water, Waste, Greenhouse, Food, Animal, Living, Sickbay, In Situ Resource Utilization (ISRU), Workshop and Energy*. As a first step, the literature on LSS and the most relevant infrastructures dedicated to LSS development were reviewed. Successively, FLaSH's preliminary study conducted in 2012 at the DLR's Concurrent Engineering Facility (CEF) was analysed. The review on the LSS and FLaSH allowed for the identification of 110 candidate technologies. Finally, a survey was carried out on 172 European entities, identified as potential participants, in order to generate primary data for the FLaSH's research opportunity study. The survey collected a total of 36 valid responses. Survey respondents revealed that 27 entities, from 15 European countries manifested a potential interest in participation and cooperation with FLaSH. The Air, Water, Waste, Greenhouse modules were identified as the most interesting. Participants' preferred methods of collaboration comprised technology testing and development as well as advisory services. The majority of the participants, 26, backboned FLaSH's dual approach of developing closed technologies for space and terrestrial applications.

Keywords: Life Support Systems, Sustainability, Human spaceflight, DLR, FLaSH.

Resumo

Esta tese tem como objetivo estudar as oportunidades de investigação do projeto da instalação Facility of Laboratories for Sustainable Habitation (FLaSH) do Centro Aeroespacial Alemão-Deutsches Zentrum für Luft und Raumfahrt (DLR). O propósito do FLaSH é a investigação, desenvolvimento e teste de tecnologias dos Sistemas de Suporte a Vida (SSV) em anel fechado para futuras missões espaciais tripuladas ou para o desarrolho sustentável do ser humano na terra. O elemento central do FlaSH é o Habitation Module Complex (HMC) e integra 12 módulos interligados, responsáveis, cada um deles, por um domínio específico na área dos SSV, nomeadamente: *Air, Water, Waste, Greenhouse, Food, Animal, Living, Sickbay, In Situ Resource Utilization (ISRU) Workshop e Energy*. A revisão da principal literatura sobre os SSV junto á análise do estudo preliminar do FLaSH realizado em 2012, permitiram a identificação de 110 novas tecnologias para serem usadas, desenvolvidas, testadas ou demonstradas. Finalmente, um inquérito foi realizado dirigido 172 entidades europeias. A análise das respostas obtidas revelou 27 entidades, provenientes de 15 países europeus que manifestaram um potencial interesse em participar e cooperar com a infraestrutura FLaSH. Os resultados sugerem que os módulos de *Air, Water e Waste* são os mais interessantes de acordo com os participantes. Os métodos de colaboração preferidos dos participantes são os testes de tecnologia e o desenvolvimento tecnológico, bem como serviços de consultoria. A maioria dos participantes suportaram a dupla abordagem do FLaSH no referente ao desenvolvimento de tecnologias de SSV em anel fechado para aplicações na Terra e no espaço.

Palavras-chave: sistemas de suporte vital, sustentabilidade, voo espacial tripulado, DLR, FLaSH.

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LIST OF ACRONYMS

ACR Advance Carbon Reactor

APCOS Aqueous Phase Catalytic Oxidation Subsystem

BLSS Biological Life Support Systems

CEF Concurrent Engineering Facility

CEEF Closed Ecological Experiment Facility

CELSS Closed Ecological Life Support System

CM Crew Member

CROP Combined Regenerative Organic Food Production

DLR Deutschses Zentrum für Luft-und-Raumfahrt

EB-F^3 Electron Beam Free Form Fabrication

EBM Electron Beam Melting

ECLSS Environmental Control and Life Support System

ESA European Space Agency

ESM Equivalent System Mass

FA Floor Area

FDM Fused Deposition Modeling

FMARS Flashline Mars Arctic Research Station

FLaSH Facility of Laboratories for Sustainable Habitation

FO Forward Osmosis

FOB Forward Osmosis Bag

HCC Habitat Control Centre

HMC Habitation Module Complex

H2020 Horizon 2020 European Commission program

ISRU In Situ Resource Utilization

ISS International Space Station

I4H Incubator for Habitation

MAV Micro Aerial Vehicle

MDRS Mars Desert Research Station

MELiSSA Micro Ecological Life Support System Alternative

MIR Russian Space Station

NHV Net Habitable Volume

LSS Life Support Systems

LMLSTP Lunar Mars Life Support Test Project

RO Reverse Osmosis

UF Ultra-filtration

UN United Nations

PET Polyethylene Terephthalate

P/C LSS Physicochemical Life Support Systems

PV Pressurized Volume

RFID Radio Frequency Identification

SARA System Analysis Space Segment

SME Small and Medium Enterprise

SCWO Supercritical Wet Oxidation

TD Technology Domain

TG Technology Group

TIMES Thermoelectric Integrated Membrane Evaporations System

TRL Technology Readiness Level

TsD Technology Subdomain

SLS Selective Lase Sintering

SLA Stereo lithography

UAM Ultrasonic Additive Manufacturing

U.S. United States

VCD Vapour Compression Distillation

VAPCAR Vapour Phase Catalytic Ammonia Removal

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"*Then I say the Earth belongs to each… generation during its course, fully and its own right, no generation can contract debts greater than may be paid during its own existence*".

Thomas Jefferson, 1789

1 Introduction

This chapter presents the synergies between the challenges to be addressed in future human spaceflight and the sustainable human habitation on Earth. Those synergies promoted the creation of the German Aerospace Center - Deutsches Zentrum für Luft und Raumfahrt's (DLR) Facility of Laboratories for Sustainable Habitation (FLaSH) initiative, which is the topic of this thesis. Moreover, it explains this thesis' context, as an internship program, in addition to its research aim definition. Finally, it describes the thesis outline.

1.1 The Space Bound: towards human exploration

Self-reliant human habitats are vital for permanent human presence in space. NASA had already established within its major goals the expansion of the humankind presence beyond Earth orbit. Future plans for returning to the Moon and Mars surface human exploration will inexorably involve long-duration human spaceflight [1]. The space is a harsh and threating environment for the human being. The radiation levels and extreme temperatures given on space together with the lack of basic resources for sustaining life present a threating scenario for the human presence.

Although several definitions exist for the edge between Earth and Space (while Karman Line defines the edge of space at 100km, in the U.S.A. humans flying over 80 km were already considered astronauts [2]) there is only one from the life support perspective: 18 km. At that height starts the so-called "physiological space" and no human life is possible without a pressurized suit or cabin since the Earth biosphere is not anymore capable of providing the required life support functions for the humankind [3]. Despite some valuable resources as water ice are present in other celestial bodies, e.g. Moon and Mars, the environment do not provide the necessary conditions for sustaining human life. Therefore, all the consumables as well as hardware for ensuring the health and wellbeing of a human crew will have to be carried from the Earth.

Mass is a critical driver in every space mission, whether is manned or not, having a high impact in the total cost of the mission [4]. For a year mission timeframe, 12109 kg in consumables are required in order to sustaining the life of a human. Materially open-loop LSS implies that all the consumables required for the year will be carried from Earth and resupplied as needed. Considering the transportation costs to LEO (Low Earth Orbit) are around U.S. 13 000 $ / kg. (Fiscal year 1994), the lunar surface U.S. 100000$ / kg. (Fiscal year 2005) are needed, then for a Mars mission they will be susceptible higher: only transportation costs of an actual human mission will become prohibitively high under materially open-loop LSS [5] [6]. Moreover, relying in earth resupply will include long waiting times and complex operations and the drawback regarding mass cost will still being present. That scenario leads to the necessity of a self-reliant habitat or infrastructure for long-term space exploration. Regenerative LSS are capable of sustaining human life with high reclamation degrees of valuable resources, i.e recycling waste products. These systems are materially closed systems and can be based in biological as well as Physicochemical (P/C) process. A high closure degree of material loops will reduce significantly the required amount of resources for a space mission. Specifically, a materially closed-loop can save up to 9000 kg in launch and 6800 kg in posterior resupplies [3].

1.2 The Earth Bound: towards sustainability

On Earth, human demand on the biosphere's (The LSS of Earth) regenerative resources is continuously increasing and has overreached the biosphere regeneration capacity [7]. The *ecological footprint* measures the demand of human population and activities place on the biospheres' regenerative resources. The *biocapacity* measures the amount of regenerative resources available on the biosphere, i.e. its capacity to regenerate.

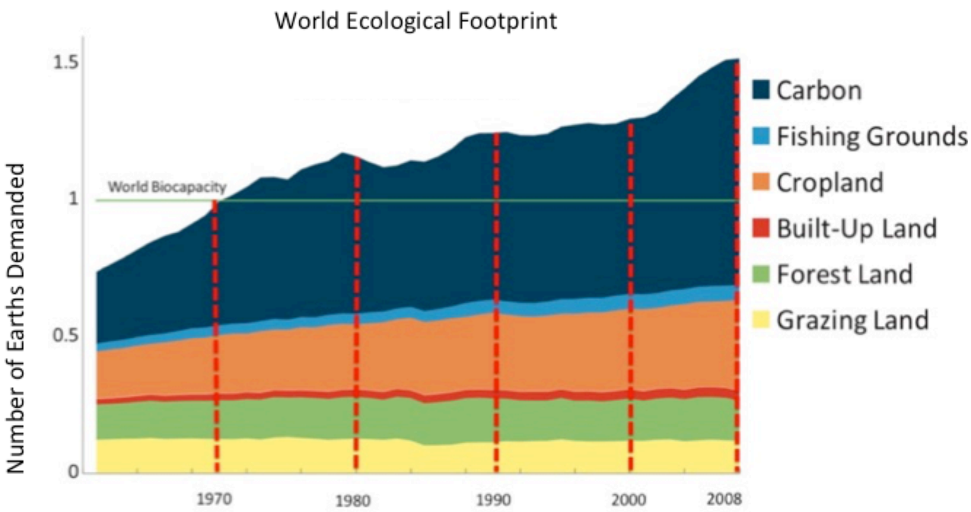

Figure 1-1:Human ecologic footprint and biocapacity in terms of planets required: [7]

The ecological footprint measured across 6 land types: crop land, grazing land (for livestock), built-up land, fishing ground, forestland, and carbon. Figure 1-1 presents the demand of human activities in term of ecological footprint and the *biocapacity* in numbers of number of planets required to face the demand. An overshot in the carbon's footprint can be observed related to the carbon's footprint, rising from 1970 and still, due to the human activities and the increase in population. The majority of the anthropogenic CO_2 is attributable to urban areas with higher impact in large cities (over 1 million habitants) and megacities (over 10 million inhabitants) [8], [9].

Regarding biocapacity, areas with ecological resource deprivation, as deserts are the most affected. Desertification can be understood as the loss of the valuable ecological resources in a landscape, which are important for sustaining life. Major catalyzers for desertification are climate variation as well as anthropogenic disturbances. Although the causes for desertification have been widely discussed without any consensus in terms of monitoring and assessment, there are facts, which are unquestionable, mentioned from now. Desertification is not a process only occurring in areas within deserts boundaries. Dry lands placed far from the desert margins are also candidates for desertification. Around 2 billion of the total population (with a 1.8 billion living in developed countries) is established in dry lands, and by 1995 about 135 million of the people living in dry lands were at risks of starvation due to the land degradation [10]. Besides, according to United Nations one-third of the Earth´s land area may turn into desert wasteland during the next years [11]. Specifically, regarding water scarcity in Europe, the 70% of the population resides in areas under water stress issues [12].

Concerned about the negative impact of conventional human development strategies in the environment, introduced in previous lines, the UN adopted the "sustainable development" strategy in 1983 for the implementation of the World Commission on Environment and Development. Sustainable development aims to enable developing strategies "to meet the needs of the present without compromising the ability of the future ". From an environmental standpoint, sustainability refers to the capability of sustaining a system without complete depletion of resources. Concerning urban areas a city becomes more sustainable with the decrease of the resource utilization to fulfill its functions. The promotion of agriculture and sustainable use of resources is the major action in order to stop, slow down or reverse desertification.

In order to advance towards sustainability involves the following considerations [13]:

- Increase in renewable natural resources and energy sources reliance.
- Reduce and / or eliminate the draw-down of non-renewable resources.
- Reduce and /or eliminate the amount and toxicity of "by-products".
- Developing ecosystems "networks".
- Utilization of human activities for tailoring the increase or ensure the stability of biodiversity rather than decrease it.
- A better understanding of the biosphere operation at a global scale in order to harmonize human activities within it.
- Provide feedback loops to the population for increasing conscience levels and awareness of the consequences of their action in the local ecosystems, and the global of the biosphere.
- Providing models of proper behaviour directed to biosphere responsibility in order to inspire and generate hope.

1.3 A space habitat for sustainability in Earth: towards FLaSH.

Parallelisms are present between essential challenges for sustainable development on Earth and the creation of LSS for long- duration human space flight: efficient resource utilization, i.e. careful handling of resources and their reutilization leading to the minimization of waste and the draw-down of the non-renewable process. Indeed, Closed Ecologically Life Support Systems (CELSS), a type of LSS as it will be explained in further sections, have been already proposed as the key for sustainable development on Earth [13]. Furthermore, the large transportation costs involved in space missions in addition to the increased difficulty of resupply operation from Earth together with volume and power restrictions make the space-based a more demanding environment. The increased demand in technology performance will increase the technology capabilities regarding terrestrial applications. From an Earth point of view Biological Life Support Systems (BLSS) provide an infrastructure for the study of the biological processes and the interaction between organism involved, with a substantially reduction in the time and number of variables, when compared to the processes timeframe involved in the Earth's biosphere, and without damaging it. However regarding space applications, biological processes are not well understood enough to exclusively rely on them [6].

In 2012, a feasibility study named as "Preliminary Study for a Facility of Laboratories for Sustainable Habitation (FLaSH)"was carried out at the Deutsches Zentrum fur Luft und Raumfahrt's (DLR) Concurrent Engineering Facility (CEF), of the Institute of Space Systems in Bremen, Germany. The objective of the (FLaSH) initiative is the creation of a terrestrial self-reliant habitat to test, mature, and improve LSS's closed-loop technologies, whether physicochemical or biological, in order to overcome the challenges of future space human exploration as well as to support the sustainable development on Earth in order to put into an end the mindset of "unlimited resources".

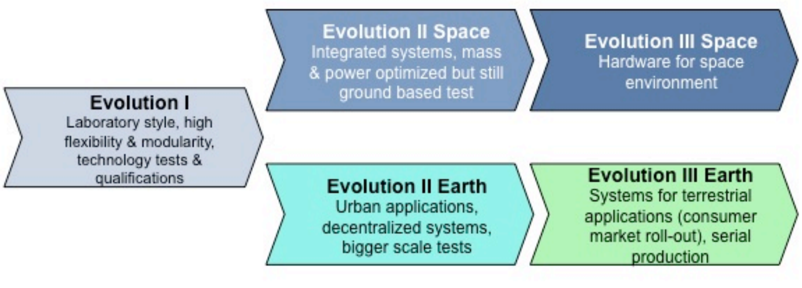

Figure 1-2: Roadmap for FLaSH development [14].

The FLaSH's evolution roadmap is presented in Figure 1-2. The first phase Evolution I, involves the implementation of the facility characterized by modularity and flexibility. At this stage research and technology maturation is considered for both space and terrestrial. The FLaSH represents the stage 1 of the project. Further on, the ambivalent approach of the facility considers the technology maturation, testing and integration according to the end user environment:

- Space Evolution steps: mass and power requirements and system integration, which are needed for all space missions. Technology Readiness Level (TRL) evaluation up to TRL level 4. Further levels in the TRL scale involve the proof of concept, component or system on relevant environment (reduced gravity or comparable to expected operational gravity environment). Unfortunately, FLaSH will not be able to perform microgravity test. That does not exclude the possibility of testing the integration of new technologies with mature ones to assess their interaction benefits and drawbacks.
- Earth evolution: terrestrial applications of closed-loop habitation. Recycling and efficient resource utilization technologies are the foundations of self-reliant habitats and key findings within FLaSH will enable innovative solutions for a sustainable living on Earth, e.g. wastewater treatment, air contaminant control.

1.4 Thesis context: DLR and the Incubator for Habitation (I4H) proposal.

This work has been carried out during a 6 months internship at the *System Analysis Space Segment (SARA)* department of the Deutschses Zentrum für Luft-und-Raumfahrt (DLR) Institute of Space Systems in Bremen, Germany.

DLR's objectives cover Earth and Solar system exploration as well as research for the protection of the environment, hence development towards environment-friendly, technological solutions for energy generation, mobility, communications and security.

The Institute of Space Systems tasks include the evaluation of complex systems covering its technical as well as economic and socio-political aspects. Further, the institute presents space-based technological solutions for scientific, commercial and safety demands in collaboration with research entities as well as the industry. The SARA department's main task is the study and evaluation of current and future aerospace systems.

This thesis is embedded within the SARA's department Incubator for Habitation (I4H) proposal "A multidisciplinary and Modular Incubator for a Synergetic Closed-Environment Habitation", written for the Horizon 2020 program. The following chapters will refer to the infrastructure as FLaSH, despite the final name approved was the Incubator for Habitation (I4H).

The Horizon 2020 program aims to provide support and funding for European research. It consists in a financial instrument for innovation; in order to tune society's needs with research objectives by addressing challenges related to energy, recycling, food safety, health care and the oceans. Further, Horizon 2020 intends to accelerate the "from the lab to the market" process. The program is directed to both academia and industry, but targets the integration of Small and Medium Enterprises (SMEs) and international based partners.

The purpose of the I4H proposal is to define and present the path of the design study for a world-class research infrastructure that responds to sustainable habitation challenges. The facility will perform as a technology incubator for LSS's closed-loop technology, processes and human activities for Space as well as Earth applications. To sum up, the goal of the design study is:

- "To present a complete technical, legal and ethical framework for the implementation of a habitation technology incubator".

Therefore, the design study will cover Horizon 2020's objectives, reaching to society's urgent needs by generating knowledge in different areas such as air and water recycling, and sustainable resource utilization. To achieve the main goal of the design study the next objectives have been defined:

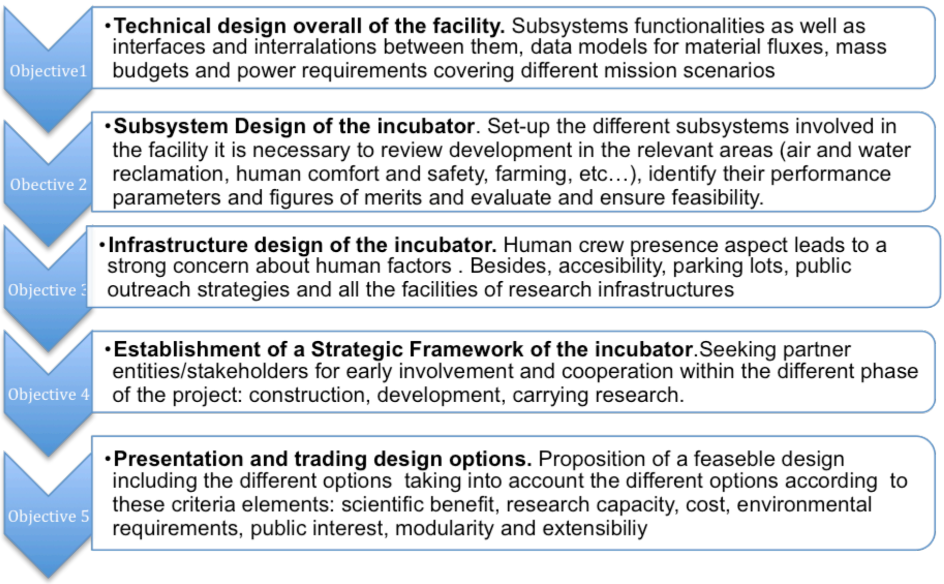

Figure 1-3: Objectives of the I4H design project proposal, adapted from [15].

A total of 5 stakeholders, including DLR, from 5 different countries, integrated the I4H proposal consortium in which DLR was the consortium's coordinator.

FLaSH will be an incubator for LSS's closed-loop technology development, testing and demonstration, yet, to this day, no specific research has been conducted in regard to the willingness, expectations and perceptions of different entities concerning a potential participation in FLASH. This research aims to fill such gap by exploring FLASH's main features and research interest, which technologies could be included in FLaSH and surveying potential participants.

1.5 Overall aim and research objectives

The main goal of this thesis is to investigate the FLaSH's research opportunity among European entities that may be interested in conducting research on the facility. Entities who may be interested in conducting research are defined as the ones whose expertise area is related with any of the FlaSH's modules. The research opportunity have been studied at three levels, being each level represented by each one of the three following questions:

(i) Are there entities interested in participation and what is their profile?

(ii) According to entities, which are the FLaSH's most interesting modules and technologies?

(iii) Which expectations and perceptions do entities have of their role within FLaSH operationalization and utilization?

In order to fulfill the overall aim it will be necessary, beforehand, to *review and study the current FLaSH configuration and identify potential candidate technologies*. This task will use as a starting point the FLaSH's preliminary study carried out in 2012. As it will be explained in the ensuing chapters, the main objective of FLaSH is to provide an infrastructure for the development, test and demonstration of closed-loop technologies for space and terrestrial applications. The main premise of the facility design is that it must enable flexibility for the exchange and functionality of systems and subsystems. Therefore, it is important at this point to examine FLaSH's current configuration and LSS's functions in order to identify other potential technological solutions that can be included. Furthermore, the results of this task supports the identification of potential participants involved in the modules functionalities and technologies, tailoring the involvement and the understanding of the profile of potential participants. It must me remarked that this work does not concern the design of the facility; instead it reviews the already-existing preliminary design of the infrastructure. The *review and study the current FLaSH configuration and identify potential candidate technologies* will provide support to proposal objectives 2 and 4, see Figure 1-3, since it will help to set up the functionalities of the modules and the technologies.

1.6 Thesis Outline

This thesis is structured as follows:

Following this introduction, chapter 2 presents a literature research on LSS. The human requirements are introduced together with a categorization of the different LSS. The end of the chapter presents an overview of the most relevant past and present LSS facilities and laboratories.

The third chapter is dedicated to the description of the initial FLaSH configuration and to the main results obtained from a preliminary study at the CEF in the Institute of Space Systems at Bremen, which will be used as a baseline.

Chapter 4 reviews and studies the current FLaSH configuration and, identifies candidate technologies, i.e new technologies that were not previously considered during the 2012 FLaSH's study. This review will be based on the LSS literature research presented in chapter 2 and the FLaSH's preliminary configuration described in chapter 3. Modules' functionalities will be described together with the current technologies considered within the 2012 CEF study, in addition to the proposal of candidate technologies.

Chapter 5 presents the study of the research opportunity. An online survey was employed for primary data generation. Key results for the research opportunity are presented and analyzed at the three, already mentioned, exploration levels.

Finally, chapter 6 presents the main conclusions of this study including future recommendations and developments to be taken.

Living in compliance with our environment, in a sustainable manner, whether in Space or Earth, is the challenge humankind must overcome and to which FLaSH initiative is committed to contribute. After all there is no better analogy of a human long-duration spacecraft as the Earth counting a total 4,5 billion years of space flight [16].

2 Life Support Systems Overview

This chapter presents a literature research on the Life Support Systems (LSS) based on the main bibliography addressing this field. First, the LSS are described from a system engineering approach, by introducing the types of LSS, the parameters with more influence in their design, the main systems involved and main functions performed. Successively, the chapter presents an overview of the main past and present LSS facilities in Space and Earth and compare them with FLaSH.

2.1 Life Support Systems Introduction

Bearing in mind the definition of the term *System,* a LSS can be defined as the set of objects which interact or have interdependence between each other in a very specific manner according to their purpose: providing the conditions for sustaining life [17].

Basic human needs as a breathable atmosphere, water, food and waste removal are natural functions carried in daily basis by the Earth's biosphere. However, in order to sustain life in Space or in specific places in Earth (e.g., underwater, remote areas, etc.) those functions carried by nature must be performed by physical or mechanical equipment, or even by a small-scale replication of the Earth biosphere [18].

The architecture of LSS varies substantially depending on the needs of the organism to be sustained and the timeframe. As an example, the LSS requirements for a manned space mission as the International Space Station (ISS) (thus for human) differ noticeably from those of a non-manned mission but with living organisms as a scientific payload as e.g. the OMEGAHAB carrying fish species of Oreochromis Mossambicus [19]. Considering the definition of the *Mission Drivers* as: "*the principal mission characteristics or parameters which influence, cost, risk or schedule and that the user or designer can control*", therefore the organism being supported represents' the LSS's main driver [20], [6].

The main purpose of this work is in line with self-reliant human habitats, thus the human is the main driver. Nevertheless, as shown in following sections, in the case of LSS for long duration spaceflight, other living organism will require a different LSS to match their specific physiological requirements.

2.1.1 LSS classification

The current section shows the classification frame for LSS. Firstly, LSS functions can be divided into regenerative functions or non-regenerative functions [6]. The LSS involve functions that are not subjected to regeneration, e.g. control or monitoring, as well as regenerative functions where resources can be reused, i.e. water, air and food. The system performing regenerative functions without resource reclamation it is referred as an open-loop system. In open-loop systems material flows into and out of the system, see Figure 2-1. The amount of resources resupplied during a mission must equal the amount of resources required by the crew. An increment in the level of reclamation of used resources turns into a decrease of the amount of resupply, i.e. a higher closure degree.

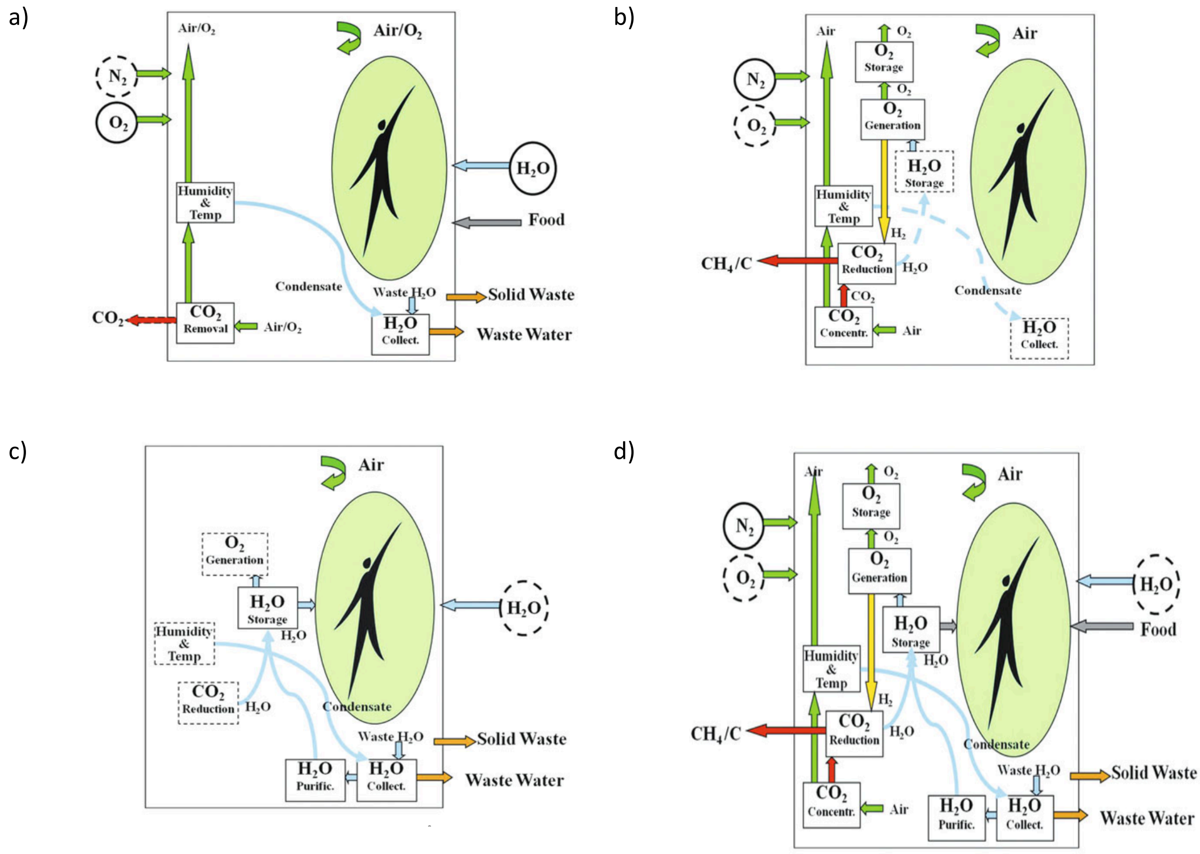

Figure 2-1:Types of LSS. On the top and left (a): an open LSS. On the top and right (b): closed air loop LSS. Bottom and left(c): water-loop closed LSS. Bottom and right (d): partially closed LSS with air and water closed loop [18].

Figure 2-2 presents the reduction of resupply mass according to the type of resource regenerated. The greatest mass saving measure is the closure of the water-loop. Increasing closure of air loops involves re-generable functions for CO_2 removal, reduction and O_2 generation, increasing power and producing residual waste as methane or carbon. However, *process water* [1]can also be used for those purposes or as an input of electrolysis unit for O_2 production. Nitrogen, or the diluent gas employed, will have to be previously stored. Combining the closure of the water loop and the air closed-loop (with H_2O as common element) results into a partially closed loop leading to 90 % in resupply mass reduction. Complete closure of a LSS requires the food loop closure. The 5 % of the remaining resupplies is due to leakage and must be balanced with the external resupply of water and oxygen.

[1] For purposes of the Clean Water Act, "Process Wastewater" means any water, which during manufacturing or processing, comes into direct contact with or results from the production or use of any raw material, intermediate product, finished product, byproduct, or waste product.

Nevertheless, higher material closure degrees come along with increase in terms of power demands, higher complexity, lower reliability and higher system mass [6], [18].

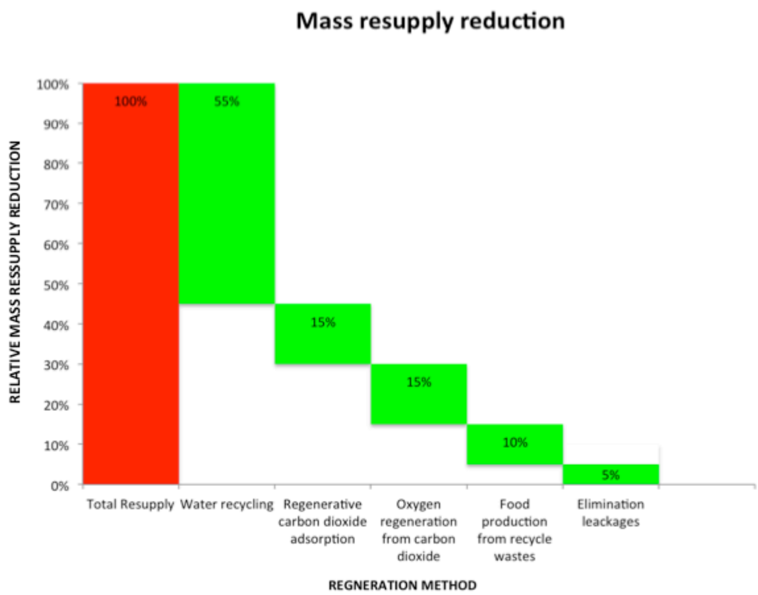

Figure 2-2: Reduction in the amount of needed resupplies with the increase of the material closure degree. (Author's adaptation from [6]).

Resource reutilization within regenerative functions can be achieved by means of two types of technologies:

1. *Physicochemical* technologies, relying in physical and chemical processes as: incinerators, distillation, molecular beds, as well as mechanical devices as fans, pumps and filters.

2. *Biological* technologies, based on biological processes including: bacteria, algae or higher plants.

A LSS involving both types of technologies is known as a Hybrid Life Support System (HLSS). A diagram regarding LSS classification is presented in Figure 2-3.

Life Support Systems for long duration missions have been the scope of several studies identifying the necessity of higher material closure degrees for reducing resupply needs and thus costs (in case of space missions) or reducing the amount of required resources for Earth–based habitats which are resource deprived [21], [22] [23]. In order to achieve a materially closed-loop habitat it is essential to close the food loop as well as the imitation of the environmental processes and functions on Earth, by means of biological systems as: higher plants or algae for in situ food and oxygen production or even animals. Such a LSS is known as Biological Life Support System (BLSS) or as Closed Ecological Life Support Systems (CELSS) and would handle all loops: air, water and food. The BLSS will also consider the utilization of physicochemical technologies as a back-up and safety systems and for non-regenerative functions.

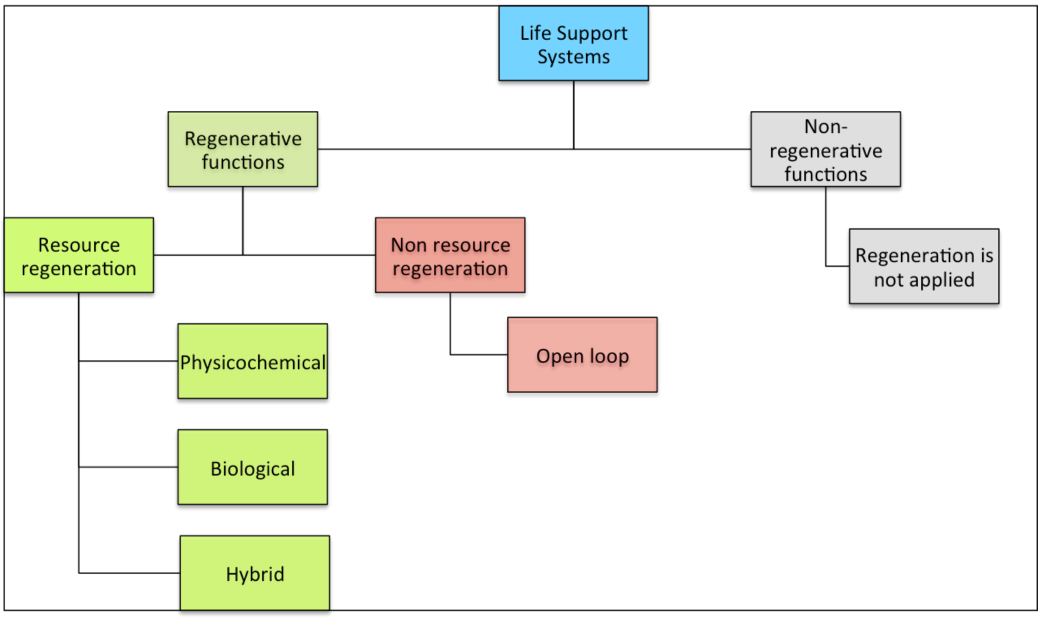

Figure 2-3: LSS classification scheme according to their regenerative capabilities.

There is not a unique-best solution among the different LSS configurations and the right decision must regard and considers the mission characteristics. Depending on the mission duration different break-even points for the total cumulative mass of the system can be obtained, regarding different LSS configurations. In Figure 2-4 different break-even points of the cumulative mass are given as a function of the mission duration and the type of LSS. For a very short duration mission, open-loop LSS are advantageous since the initial mass of P/C LSS with regenerative functions is higher than in the case of non-regenerative. The first break-even point occurs with P/C LSS including regenerative life support technologies. Usually this break-even point occurs for durations higher than two weeks [24]. For long-term missions hybrid LSS, i.e. combining biological and P/C technologies, require less mass than P/C with regenerative functions. Finally, for very long duration missions (more than 5 years) the CELSS are the best option. Developing and establishing a CELSS on Mars or on the Moon involve a higher complexity level than a P/C LSS. In fact CELSS involving a 50% of food loop closure will be only feasible for 5 to 7 years missions while at least 11 to 12 years will be required to justify a 95% of food loop closure. For the last case mission duration can be reduced by increasing the mission crew, specifically a breakeven point between the 50 % food loop closure and the 95 % can be obtained in 6 - 7 years with a crew of 20 or more [6], [18]. Nevertheless, the exact determination of the cumulative mass' breakeven points between the different types of life support systems requires the knowledge of the life support technologies properties to be employed and the mission scenario and assumptions [6].

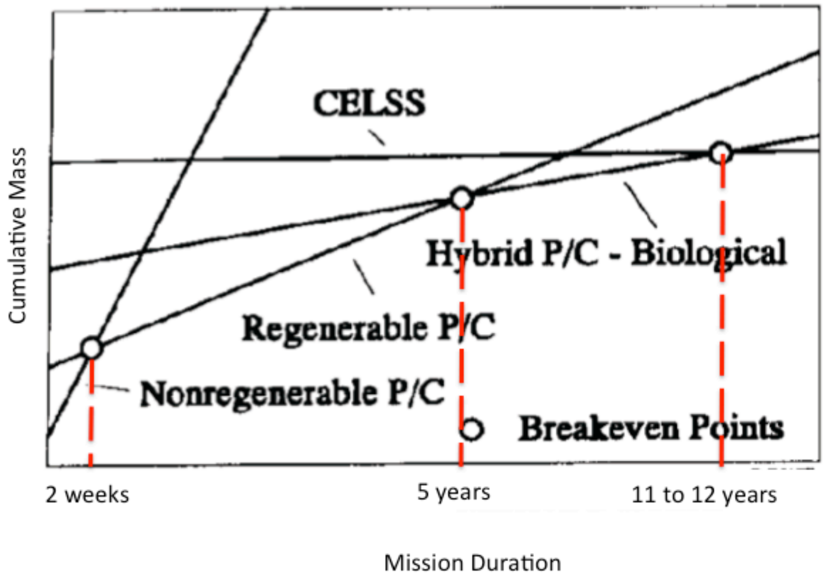

Figure 2-4: Break-even points in the cumulative mass for different LSS configurations [6].

Mission drivers and its impacts on LSS's design are presented in Table 2-1 .

Table 2-1: Mission drivers and its impacts on the LSS's design [24], [6].

Mission Drivers	Effect on Life Support System Design
Crew size	More consumables
Mission duration	More consumables and increased reliability
Cabin leakage	Increase resupply
Resupply capability	Difficult resupply: store consumables and demand of reliability
Power availability	Limited power drives to passive or low-energy systems
Volume availability	Restrictions of space drive to more volume-efficient systems
Gravity	Selected processes must work in anticipated gravity
Contaminant source	Contaminant requires counter measures and a more robust system
Using in-situ resources	Decreases resupply needs

2.2 The human system

Given the relevant role of the human, as the main driver, in the LSS's design process it must be integrated within the rest of the systems. The human requirements do not only cover the physiological necessities (regarding the physical conditions of the human body) but also psychological ones (regarding the behaviours of the human). Therefore, the human requirements as an integral part of the LSS have to be studied. In rough numbers, a human can survive 4 minutes without oxygen, 3 days without water and close to 1 month without food. Oxygen, water and food are considered the main and basic consumables for ensuring human life as already suggested at the beginning of this chapter. However, the LSS must guarantee additional environmental standards to support the human health and wellbeing during the whole mission (i.e. during duty and off-duty times). The addition of environmental standards leads NASA to refer LSS as Environmental Controlled Life Support Systems (ECLSS). Those environmental standards are referred under the term of *habitability* in and [5], [24].

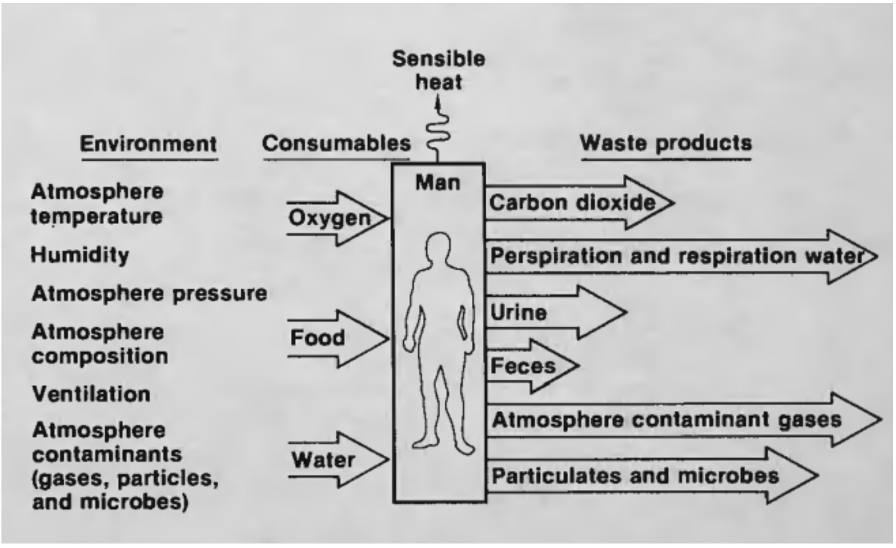

Figure 2-5: Human basic life support needs [25].

Habitability aspects can be divided in two basic levels according to [6] [26]: *basic habitability* and l*ong-term habitability*.

In Figure **2**-**6** it is presented a comprehensive diagram with classification of the habitability aspects:

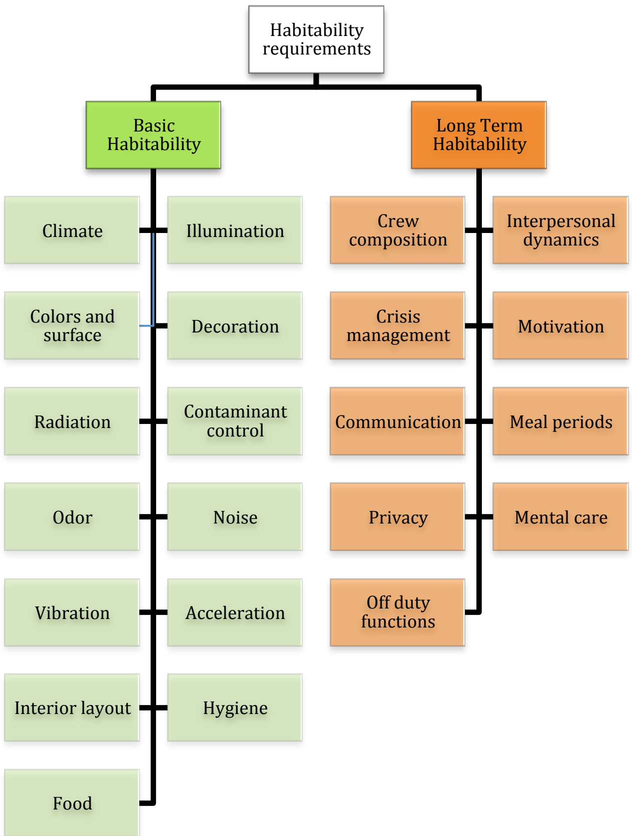

Figure 2-6: Habitability aspects classification (adapted from [6]).

As it can bee seen in Figure **2-6**, basic habitability covers physiological needs (e.g. noise, vibration climate, food and so on) whilst the long-term habitability focuses on psychological issues (e.g.: privacy, mental care, off duty functions and so on). It must be remarked that basic habitability aspects are also addressed in long-term habitability. They are not repeated in the long-term habitability branch in order to provide a better appreciation of the aspects to be addressed on long duration missions.

The human metabolic requirements are provided in Table 2-2. It must be remarked that physiological and psychological aspects are strongly related. For example, if the habitat is not under proper lighting conditions it can be a source for working errors, sleep disruption and break of circadian cycles (physiological aspects) leading into irritability and morale decrease (psychological aspect). A complete analysis of the human requirements is out of the scope of the work and therefore will not be further developed in this work. A synthesis of the human physiological and psychological requirements based on current literature it is provided in Appendix A. Human requirements.

2.2.1 Metabolic Rates

The amount of consumables required for the crew members are determined by their metabolic rates. In this subsection the metabolic rates will be addressed since they are the tool for identifying the basic needs in consumables of the crew members and are presented in Table 2-2, [6], [14].

Table 2-2: Physiological inputs and outputs.

Input Consumable /day	Amount per CM		Output Consumable / day	Amount per CM	
O_2 [kg]	Total	0.84	CO_2 [kg]	Total	1
H_2O [kg]	Drinking	2	H_2O [kg]	Respiration	1.83
	Content in food	0.75		Waste water	6.8
	Food preparation	1.15		Waste water from cloth washing	0.891 -12.5
	Personal cleaning	6.8			
	WC	2		WC	2
	Cloth Washing	0.891-12.5[2]			
Food [Kcal]	Man 70 kg.	2971	Urine [kg]	Total	1.63
	Woman 45 kg.	2160	Faeces [kg]	Total	0.253

2.3 Life Support Systems basic functions

This subsection is dedicated to provide an insight of the main functions involved in a LSS, summarized in Table 2-3, [27], [22] [23]. The number of systems included varies according to the configuration of the habitat and to the missions' requirements. The LSS can also include EVA (Extra-Vehicular Activity) operations implying the study of the suit, the metabolic rates during EVAs, radiation requirements and medical stations [3], [5]. However EVA's LSS are out of the scope of this study.

The biological or P/C technologies capability to carry the LSS functions is evaluated in Table 2-4. Biological processes are not able to carry out the necessary non-regenerative functions and thus a specific number of functions within a CELSS relay on physicochemical technologies.

[2] The author noticed a remarkable variation in the laundry's water requirements for the different sources accessed. This high variation is due to the laundry technological option considered.

Table 2-3:Life Support main systems and functions carried.

Life Support System	Description	Functions
Atmosphere	Monitoring and control the atmosphere composition, pressure, temperature and humidity, atmosphere regeneration, and fire detection and suppression	• Provision of O_2 • Provision of N_2 (or diluent gas) • CO_2 removal and reduction • Pressure control • Ventilation • Trace contaminant control • Temperature and humidity control • Fire detection and suppression
Water	The water subsystem is in charge of ensuring the water necessities of the crew. Allocate the necessary equipment for potable, hygiene and urine water reclamation.	• Provision of potable water • Provision of hygienic water • Urine treatment and reclamation • Potable & grey water treatment • Water quality monitoring
Waste	The waste subsystem will receive waste from the whole habitat, it will condition and prepare for storing (sterilized, odour removal for storage), will process for reduction and reclamation when possible	• Waste conditioning and storing • Waste processing • Waste decomposition
Food	Food provision, storage and processing	• Food provision • Food processing • Food preparation • Food storage
Crew safety	Ensuring crew health and safety	• Radiation protection • Fire suppression when not included within atmosphere management.

That is the case for the Atmosphere and Water subsystem where the biological process can carry all the regenerative functions except the monitoring and control functions. Biological processes for atmospheric and water regeneration purposes must implement measures for counter microorganisms' increase that can contaminate air in closed and small self-reliant habitats.

Bioregenerative Food subsystem is capable of food generation by means of agriculture or aquaculture. However, some products collected are raw products and need further processing to make them suitable for the human digestive system (e.g. grinding cereal grain for flour production and using the flour for pasta production). Food processing function, storage and preparation rely exclusively on P/C technologies. Another limitation concerning biological processes is found in the inorganic waste processing and reduction. By solid inorganic waste reduction it is considered: spare-parts, metal, filters, inorganic salts, and so on, generated within the habitat as stated in [23], [14].

Table 2-4: Capability analysis of P/C and biological technologies for life support functions. Colour code: red denotes "non-capable" and green denotes "capable". The "Y" stands for Yes and the "N" for No.

System	Function	Regenerative [Yes/No]	P/C	Bioregenerative
Atmosphere	Provision of O_2	Y	green	green
	Provision of N_2	Y	green	red
	CO_2 removal and reduction	Y	green	green
	Atmosphere pressure control and ventilation	N	green	red
	Trace contaminant removal	N	green	red
	Particulate removal	N	green	red
	Temperature and humidity control	N	green	red
Water	Water provision	Y	green	green
	Hygiene and potable water treatment	Y	green	green
	Water monitoring	N	green	red
Food	Provision	Y	red	green
	Preparation	N	green	red
	Processing	N	green	red
	Storage	N	green	red
Waste	Storage	N	green	red
	Processing: solid- non organic waste reduction	Y	green	red
	Processing: solid- organic waste reduction	Y	green	green
Crew safety	Fire detection and suppression	N	green	red
	Radiation protection	N	green	red

2.4 Overview of FLaSH's similar infrastructures

Last sections provided a holistic understanding of the LSS, main systems involved as well as functions carried within them. This subsection overviews LSS infrastructures similar to FLaSH on both environments: space and Earth. The Earth-based or terrestrial LSS facilities include: underwater habitats, space analogues, remote areas research stations and Closed Ecological Life Support Systems (CELSS). The space-based facilities comprise orbital stations for extended human presence in space. The studied features of each facility include mission drivers with impact on the LSS's design, as it has been listed in Table 2-1, and other LSS relevant data in regard to the resource regeneration and closure indexes. In specific: the crew size, mission duration, the floor area (FA) per crew member, in gravity environments, or the pressurized volume (PV), in microgravity environments, the utilization of regenerative life support system and the closure degree when available. The main results obtained from this study are summarized and listed in Table 2-5.

2.4.1 Underwater habitats

Due to the lack of some of the resources necessary to sustain human life (e.g. atmosphere) underwater habitats present analogous characteristics to space habitats such as:

- Pressurized habitable space.
- Limited re-supply capacity.
- Necessity of atmospheric revitalization and monitoring.
- Dramatically consequences due to power loss.
- Confinement and isolation.

Nevertheless, the underwater environment comprises advantages for LSS functions provision in contrast to the space environment. Being surrounded by sea allows in-situ seawater utilization for water supply and oxygen (through water electrolysis). Furthermore, surrounding hydrostatic pressure avoids atmosphere leakage, and power supply is not as limited as in space.

The study of underwater habitats concluded that the Conshelf III provided the lower performance in terms of area available per crewmember: 5,4 m^2. The highest value of floor area per crewmember was found for the BIOSUB habitat (9 m^2). The Aquarius habitat it is the second lowest in terms of area available per crewmember with a total of 7 m^2. The Aquarius habitat, in addition of being an underwater habitat, it is also a space analogue (space analogues category will be introduced further on this section) employed within the NASA Extreme Environment Mission Operations program (NEEMO). Nowadays, the habitat is used as test bed for astronaut training in EVAs and research on the isolation and confinement effects on humans [28].

Regarding the LSS's regeneration capability only the BIOSUB underwater habitat addresses reclamation with regenerative life support functions as CO_2 absorption and O_2 generation by means of bioregenerative technologies (i.e. algae coil) [29]. The rest of underwater habitats provided LSS functions under open-loop conditions. Regarding crew composition, numbers vary from 2 to 6 crewmembers per habitat, being Conshelf-III and Aquarius the habitats with higher capacity regarding crew size.

The research objectives of underwater laboratories involve the impact of human presence in underwater ecosystems, underwater ecosystems and biodiversity and drilling techniques as well as the study of human behavior for long-duration spaceflight. Only the BIOSUB addressed the demonstration of algae reactors for atmosphere regeneration purposes.

2.4.2 Closed Environmental Life Support Systems (CELSS).

As previously stated, Closed Ecological Life Support System (CELSS) are materially closed but energetically open systems based on biological processes. The CELSS recreate a similar LSS to the

Earth's biosphere than physicochemical systems although it must include physicochemical systems for control and monitoring, as pointed out in Table 2-4.

The major constrains when studying huge systems as the Earth's biosphere are the extremely long periods necessaries for closing the loops (food, air and water) and the high number of variables involved. As an example of the advantages of CELSS for studying ecological processes, in Biosphere 2 the conversion of all the facility's CO_2 into plant life occurred 8000 times faster than in the Earth's biosphere [6]. CELSS provide a small-scale test bed for a better understanding the interaction between species, permitting to control variables and evaluate their impact on the system. Besides, direct experimentation on Earths' biosphere could lead into damaging it, placing CELSS on of the best tools for ecological research.

Within all the CELSS studied it is present the reclamation of resources in regenerative functions. The main goal for all the habitats presented in this section is the demonstration of a closed-loop habitat based on bioregenerative technologies and the study of ecological processes within reduced ecosystems.

2.4.2.1 Biosphere 2.

Amongst all the CELSS under study, the Biosphere 2 is the most important and extensive project, hence a greater attention is dedicated to it, see Figure 2-7. The Biosphere's 2 major goals include:

- Determine how self-regulating is a biosphere system by clarifying laws of biospheres.
- Create the infrastructure for designing, build, operation, consult and managing artificial biospheres for both Earth and in space and study ecological interactions to provide knowledge in life systems for terrestrial applications.
- To support possible human positive ecological impact on Earth's biosphere.

Biosphere 2 consisted in a manmade biosphere, hosting 8 crewmembers for a period of 2 years. The facility enclosed in its 20000m³ volume (14000 m² in surface) seven biomes distributed in two major areas "the wilderness area" and the "human area". The "wilderness area" included 5 biomes: rainforest, savannah, desert, ocean and marsh. The biomes on the "Human Area" were: human and intensive agriculture. Over a total of 3000 thousand documented species of plants and animals were included in the facility. The human biome enclosed the following facilities: apartments, analytical laboratories, medical facilities, veterinary facility, kitchen and food processing equipment, computer workstations, workshop and maintenance room, recreation and fitness areas. Biosphere 2 also included mechanical systems to perform water and air circulation as wells as heat exchange.

The facility endured two closure experiments being the first one the most relevant with a total duration of 2 years: from September 26th,1991 to September 26th ,1993.

The most significant results from the two-year closure experiment are summarized below [30]:

- Nutrition and crew physical health: by the end of the experiment crew members lost an average of 12 kg (for man) and 8 kg (woman) due to calorically restricted but nutrient dense diet which was basically vegetarian. Far from being unhealthy, comparison between pre and post closure medical data confirmed retarding of aging and expansion of life span due to the type of diet followed.

Figure 2-7: Biosphere 2 facility [31]

- Psychological wellbeing and Crew interaction. Support from mission control together with contact with family and friends were found to be a very effective measure for emotional and psychological stress relief. It must be remarked that the crewmembers could establish contact via exterior in real time. Future long duration and planetary space missions should to take into account that communication delays will be a source of stress to the crew. Furthermore, there was an important fact that psychologically motivated the crew in order to keep going through the mission, as a stated by crewmember Jane Poynter: “I knew I could walk out the airlock door at any time, if it really got bad”. A motivational thought not to be considered in space missions.
- The experiment also served to study the effects of confinement and isolation on humans, interpersonal relations and their effects on crewmember stress and performance.
- Carbon dioxide level fluctuations during day and night and seasonally, increasing during day and summer. Fluctuation were due to plant photosynthesis process in which the increase of light lead to a major consumption of CO_2.
- Biosphere 2 endured serious and unexpected problems regarding the stability of oxygen levels. After the first forth months oxygen concentration levels decrease from a 20,4 % (found in Earth atmosphere) to 18 %. The lowest pick in oxygen concentration was slightly lower than 14 % and occurred in January 1993. Oxygen had to be injected into the facility since those low levels presented a hazard for human health. The decrease of 0,9% in oxygen concentration was attributable to the fact that big areas of the facility were built on concrete. High amounts

of CO_2 reacted with calcium hydroxide, present in concrete, to form calcium carbonate and water instead of being used by the plants for O_2 generation.

- Material cycles. The intensive agriculture biomes hold a major role in the dynamics and equilibrium of oxygen, carbon and the different species of nitrogen within and between biomes.
- Plant diversity. Most plant species persisted since closure. Dominance patterns occurred within the dessert biome.

Despite completion of the mission and the great amount of knowledge generated in the fields of life and Earth sciences, the project failed to achieve a self-regulating biosphere system. Currently Biosphere 2 is a facility of the department of the University of Arizona dedicated to environmental research and public outreach.

2.4.2.2 Closed Ecology Experiment Facility (CEEF) .

The Japanese CELSS, known as Closed Ecology Experiment Facility had undergone several closure experiments between 2005 and 2007. The maximum closure was achieved in 2007 and accounted for 21 days with 2 crewmembers (men) and 2 goats. The goal of including two goats was to evaluate the integration of animal husbandry (necessary in the LSS for long duration space mission) within a CELSS. The facility included a Plant Cultivation Module (PCM) that intake CO_2 from the Animal holding and Human Module (AHM) to provide crewmembers and goats with food and oxygen Furthermore, waste processing techniques were applied as pyrolysis of human / goat feces and urine as well as for the inedible part of plants (not used for feeding goats) followed by incineration of the resulting carbonized feces /urines and inedible plants. Waste processing material unbalances required the external injection of oxygen, thus opening the loop [32]. This facility is the lowest in mission duration and crew amid all the studied.

Major research areas of this group were bioregenerative technologies, food production, human isolation and confinement, and diet investigation [33].

2.4.2.3 LUNAR PALACE 1.

China has been also developing their own CELSS initiatives for planetary missions and long duration spaceflight: the LUNAR PALACE 1 (Lunar Integral Experiment Facility for Permanent Astrobase Life-Support Artificial Closed Ecosystem). In May 2014 three "econauts[3]" finished a 105 days closure period, the maximum endured within the facility until today. The 55 % of the food consumed by the econauts was generated within the habitat while the remaining 45% was externally generated. The internally produced food included 5 types of cereals, 15 types of vegetables and worms as the main

[3] Name traditionally used in literature to refer crew in CELSS.

source of protein intake. The habitat addressed water and air regeneration. Wheat was the main oxygen regenerator. Unfortunately, any of the sources accessed specified water regeneration technologies. The facility comprised a 58 square meter vegetation cabin and a 48 square meter living cabin with a dining room, bathroom, a disposal room and three beds [34].

2.4.2.4 Lunar Mars Life Support Test Support Project (LMLTSP).

The Lunar Mars Life Support Test Support Project represented early efforts of the Advance LSS program towards the construction of the ALSSIT (Advance Life Support Systems Integrated Test bed) previously known as BIO-PLEX. The tests were conducted within the Advance Life Support Systems Test Bed (ALSSTB) facility and, as seen in Table 2-5, is the smallest facility amongst the CELSS with an available habitable area of 21 square meters. In September 19th, 1997 the Phase III experiment involved 4 crewmembers within a habitat for 91 days combining regenerative biological as well as physicochemical technologies in order to achieve 100% closure in the water and air cycles. In addition to the externally generated pre-stored food, wheat grain for bread baking and fresh lettuce was internally produced within the facility. Waste processing facilities included feces incineration with fluidized bed reactor. The resulting CO_2 was regenerated for growing wheat. The LMLTSP proved feasibility of a hybrid life support system capable of achieving high closure degrees in air and water loops.

2.4.2.5 BIOS III

BIOS III (Russia) was built in 1973 in Siberia. Antecessor systems of the BIOS III were BIOS I and II, which back in 1968 already achieved 85% of closure by combination of biological and physicochemical systems for oxygen and water regeneration. Indeed, in 1969 three crewmembers lived for one year under complete closure of water and air loop, including plants for vitamins providing.

BIOS- III consists in a sealed structure with four main modules: three chambers for plant growth which provide crewmembers with up to the 80 % of food they consume (those chambers are known as Phytotrons) and a fourth module containing living facilities, control and monitoring infrastructure. The main goal is to provide full regeneration of water and air in addition to some nutrients within a complete isolated facility. Crewmembers inside will perform all required maintenance tasks for the proper operation of the facility.

The facility volume is 325 m^3 and covers a surface area of 131 m^2, with 31.5 m^2 available per module. Two of the three plant modules are dedicated to hydroponic higher plant cultivation and the others are for algae cultivation. Research has been continuously performed within the BIOS III although only three full-scale closed loop experiments have been carried out. The 1972-1973 was the test run with longer duration accounting closure for 6 months hosting 3 crewmembers. Between 1983 and 1984 was achieved the highest closure level with a 91% of closure during a 180 days experiment involving 2 crewmember.

2.4.2.6 Micro-Ecological Life Support System Alternative (MELiSSA)

Despite not been included in the similar facilities study due to the absence of human crew the MELiSSA (Micro-Ecological Life Support System Alternative) pilot plant is worth to mention as an ongoing project regarding CELSS within Europe and coordinated by ESA. Based in an "aquatic" ecosystem it is intended to address bioregenerative food production, water and oxygen from waste, carbon dioxide and minerals [35]. The recycling system is distributed in five compartments. Three of them are dedicated to waste reduction by fermentation process, another compartment with algae or plants for food production, oxygen and water and a last compartment dedicated to host the crewmembers. In 2009 a pilot plant was already designed for concept demonstration with animals. It is expected that the project will include a human crew before 2025. The MELiSSA project is divided in 5 phases including: basic research & development, preliminary flight experiments, ground and space demonstration, technology transfer and education.

2.4.3 Space Analogues

In long-duration missions the isolation and confinement along with the potential hazards and risks are highly influenced by crew autonomy due to: the lack of resupply, reliance between crewmembers, sleep disturbance, mechanical breakdowns, poor quality and delayed communications. Earth based Space Analogues are a tool for preparing and learn to cope with those long-duration mission related aspects and minimize the risks derived from them. It must be remarked that all the Earth-based infrastructures presented in this work are, in fact, space analogues, since they involve features or are placed in environments that emulate, at some extent, the living conditions of space. Nevertheless, in this work only infrastructures with the specific purpose of recreating planetary living conditions have been considered as space analogues.

2.4.3.1 Mars Analogs Research Stations (MARS).

Mars analogues are defined as locations on Earth where some environmental conditions, geological and biological features are similar to those encountered in the past or present on Mars [36]. The Flashline Mars Arctic Research Station (FMARS), in Devon Island in the Arctic, and the Mars Desert Research Station (MDRS), in Utah, are laboratories to learn how it would be living and working on Mars. Both stations provide a prototype of the habitat that will be used in future human Mars exploration missions and have been designed considering that they will have to fit within a space transportation system like a Saturn V launcher. Hi-SEAS is also a Mars analogue placed in Hawaii with similar features to the previously presented analogues but offering a higher habitable area per crewmember up to 23, 8m^2. A dome and a workshop module integrate the Hi-SEAS habitat.

Mars 500 represents the most extensive space isolation simulation of a Mars human mission, simulating the phases of a two-ways trip to Mars, with a planetary EVA operations included. Experiences made on the Mars 500 integrated a mission crew composed by 6 male components: three Russians, one Chinese and two Europeans. Despite the facility operated under open-loop conditions it provided with an extensive knowledge regarding psychological as well as physiological aspects of human confinement and isolation for long duration spaceflight.

As seen in Table 2-5 all analogues overviewed in this work operate with the same crew size: 6 members, following recommendations established by Mars and long duration spaceflight reference missions [37], [38], [39].

Despite delivering valuable data for future long duration space flight in the fields of crew selection, psychology and behavior, mission planning and operation as well as tool testing (like spacesuits), space analogues do not address material closure.

2.4.4 Remote areas research stations

Remote areas research stations category involves essentially polar research bases and vessels. A total of 47 of research stations are located in the Arctic and Antarctic areas. Due to the extreme climatological conditions and geographical situation, polar research stations present a similar scenario to be found in planetary bases, placing them as space analogues but with the difference that their main purpose is not the space exploration. Polar research station, as well as planetary bases, are characterized by: scarcity of fresh food, cramped living conditions, lack of social relations, sensory deprivation, isolation, remoteness, re-supply difficulties, monotony and limited times out of the habitats amongst others. Those conditions make polar research stations the object of study of space psychological aspects of isolation and confinement [40], [41], [42], [43] among others as: environmental research, astronomic observation, technology development and medical studies [44], [45]. Furthermore, zooning considerations were in the Concordia polar research station by separation of the available space in two different modules in order to separate noisy and quiet functions and activities.

The Concordia Base station must be self-reliant during the winter season, approximately 9 months, accommodating a crew of 16 members. The Neumayer III is also a research station located at Antarctica, operated by 9 members for at least 8 months. For space mission application, winters are the most interesting season at polar research stations since habitats must be completely self-reliant. The weather and remoteness make impossible resupply operations. Therefore, Table 2-5 lists mission periods and crew size for remote area station only for wintertime.

The long periods of isolation endured in those outposts makes of interest the implementation of resource reclamation technologies in order to avoid resupply. An example is the case of the Concordia which includes a bioregenerative LSS for black water regeneration and physicochemical technologies for grey water reclamation [46]. The main drawbacks of polar research station, analogues and submarines for space LSS development is the presence of gravity and the fact that they are not short in air and in some cases water (Antarctic coastal posts). However, these drawbacks do not prevent them of benefiting from space LSS to increase their reliance. As previously mentioned, this is an example of Earth resource deprived location where the application space LSS can help to improve the quality of life.

2.4.5 Orbital facilities

Finally, this work presents the most relevant LSS facilities in space. From the historical flight of Yuri Gagarin in April,12th 1961 onboard the Vostok space capsule until nowadays, space LSS have endured a transition from open-loop to partially closed systems. First manned spaceflights onboard Vostok and Gemini capsules or even Apollo spacecraft (command module and lunar module) did not last more than 15 days. As it has been explained in the previous sections, for short duration missions open-loop LSS are preferable due to the mass and reliability penalizations of regenerative life-support systems.

The Salyut-1 (1971) was the first space station offering the possibility of long stays in space. Salyut-6 and Salyut -7 implemented a water recovery system from condensate, in order to recover potable, and hygienic water recovery (grey water). Besides, regenerative systems for CO_2 removal (despite that the CO_2 was stored and vented) were also used [47]. Waste management in Salyut consisted in the storage and ejection to the space once per week.

The Skylab (1973) was first United States' space station. The station hosted crew sizes of 3 astronauts for 84 days offering a pressurized volume of 93,4 m^3 per astronaut. Skylab was the first space station including regenerative technologies for CO_2 by means of two molecular sieves canisters. Water processing was not addressed and wastewater was vented to the space. Waste processing included collection, stabilization and storage of feces and urine.

The Spacelab facility represented early European efforts in space stations. It was designed to fly onboard the Space Shuttle. Taking into account that the life support functions were already provided by the Space Shuttle, the Spacelab LSS tasks consisted in air ventilation, monitoring and control while astronauts were inside.

The Space Shuttle's CO_2 removal system was based on lithium hydroxide canisters. Wastewater and urine was stored and vented. Waste, as feces, was dried, stored and returned to Earth on board the Space Shuttle.

Table 2-5: Properties and characteristics of earth- based and space-based similar facilities [48] [49] [50] [51] [52] [53] [54] , [55], [56], [36], [57], [58], [59], [60], [61], [62], [3], [63] [64], [65], [66]

Environment	Name	Crew	Mission time [days]	FA [m²] or PV[m^3]	Loops with closure	Closure Index [%]
Underwater Habitat	TEKTITE I & II	4	60	7,2	None	0
	La Chalupa	4	30	5,7	None	0
	ConShelf-III	6	21	5,4	None	0
	AQUABIO	1	12	9	Air & water	10
	Aquarius	6	14	7	None	0
CELSS	CEEF	2	21	24,6	Water, Air, Organic Waste	80
	Moon Palace 1	3	105	40	Water, air & food	90
	LMRS	4	91	21,9	Water, air & food	90
	BIOS-III	3	180	31,5	Water, air & food	91
	Biosphere 2	8	730	1750	Water, air & food	80
Analogue testing	Mars 500	6	500	35	None	0
	MDRS	6	14-30	20,6	None	0
	HI-SEAS	6	120	23,8	None	0
	FMARS	6	122	15,5	None	0
Remote Areas	Concordia	16	270	93,8	Black Water (Biological) & Grey Water (Physicochemic al)	Not available
	Neumayer III Station	9	270	205,6	None	0
Orbital	Salyut	3	230	30	Water & Air	Not available
	Skylab	3	84	94,3	Water & Air	Not available
	MIR	3	180	130,7	Water & Air	Not available
	ISS	6	180	152	Water & Air	100% air loop 63% water loop

The MIR was the first real long-term habitation space station started operation during 1986 and was continuously occupied until 1999. In 2001 the MIR ended its space endeavor when deorbited, reentering on Earth [67]. The MIR's LSS addressed atmosphere and water regeneration. However, it required from food, water and nitrogen resupply. Regarding water regeneration MIR's LSS was able to recover potable water from condensate. Hygienic water was recovered with multifiltration techniques. Urine wastewater was processed on a Vapor distillation and filtration, attaining an 84% of water recovery from urine reclamation. Reclaimed water was used for oxygen generation from water electrolysis. The CO_2 was captured by regenerative technologies. However, the hydrogen (resulted from water electrolysis) and the captured CO_2 were vented in to space.

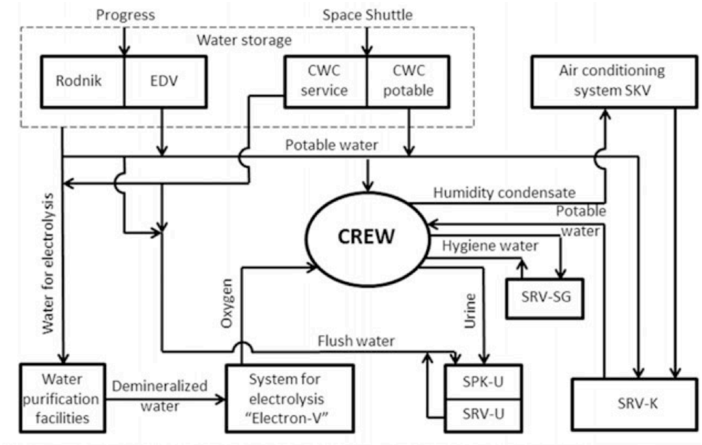

Figure 2-8: MIR life support systems architecture [18].

Nowadays, the ISS is the only space station in service and more than a space infrastructure it represents a symbol of global cooperation. The first launched element of the station was called Zarya and belonged to Russia. Currently, the ISS accounts with the Russia's contribution (with the Zarya control module and Zvezda service module), United States (Destiny laboratory), Europe (Columbus module) and Japan (Kibo module). The ISS is designed to serve mission crews of up to 6 members and more during crew exchange periods. Initially, the LSS's designed architecture was a partially distributed between the U.S and the Japan and the European modules. However, after including Russia as a partner, the design evolved into a more centralized LSS. Nowadays, there are available 2 complete LSS for the whole station. The Russian LSS is distributed between the Zvezda and the Universal module. This LSS is the same used in MIR, see Figure 2-8, and it was designed for the MIR 2 station. The other LSS is installed on the of U.S. Destiny's Laboratory and Node 3 Tranquility modules. The rest of laboratories and modules only address LSS functions for humidity and temperature control, air circulation and fire detection and suppression. In terms of the closure index, the ISS achieves a 100% of air regeneration and reclamation. Despite water is completely reclaimed waste water is used for water electrolysis in order to generate oxygen reducing water closure loop down to 63% [68].

Research carried in the space-based facilities involves several fields: life sciences, earth observation, life and physical sciences and studies of microgravity environment [69] [70] [71].

2.5 Conclusions

The literature review exposed that for the design of human spaceflight LSS the main driver is the human. The main 5 life support areas involve atmosphere, water, food, and waste and crew safety management. For extended human presence in space the LSS must also address human habitability requirements including the psychological aspects involved in long duration spaceflight.

Long duration missions' LSS must address resource regeneration, closing air and water loops by means of regenerative technologies. Closing the water loop is the greatest mass saving measure, with a decrease of 55 % in needed resupply mass. Regeneration can be achieved by technologies based on physicochemical as well as biological processes. Physicochemical technologies present higher reliability and lower complexity than technologies based biological processes but CELSS became essential in order to close the food loop and achieve material closure degrees up to 95%. Non-regenerative physicochemical technologies are not recommended as main LSS technologies for long duration spaceflight since they do not address resource reclamation and increase the necessity of resupply. However, their high reliability and lower complexity places them as the perfect candidates for emergency situations.

3 The Facility of Laboratories for Sustainable Habitation (FLaSH)

Presented the literature research carried on LSS, which involved the description of their main characteristics and the areas where they have been applied, this chapter is focused on the description of the initial configuration of FLaSH. It must be remarked that FLaSH system is at a very initial design phase. In 2012 a preliminary study was conducted by DLR within the Concurrent Engineering Facility (CEF). This chapter highlights the main outcomes of that preliminary analysis that are of interest for this thesis, specifically the Habitation Module Complex (HMC), see Figure 3-1.

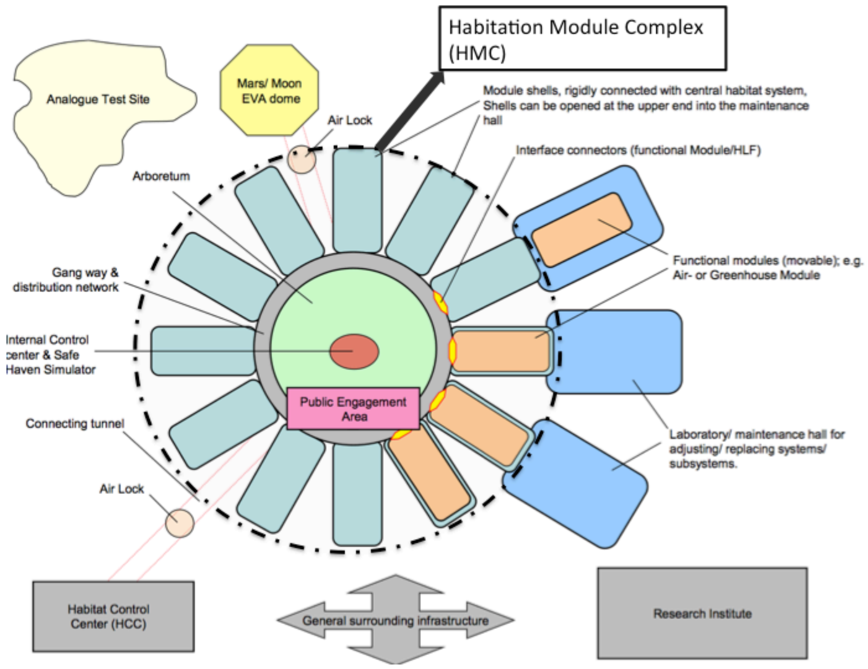

Figure 3-1:FLaSH's initial configuration. The FlaSH is integrated by the Habitation Module Complex (HMC), the Habitation Control Centre (HCC) and Extra Vehicular Activity (EVA) simulation areas. The EVA areas are also considered to be included within the Arboretum dome (green coloured dome at the centre of the image) [72].

FLaSH consists in 4 main areas: the Habitat Module Complex, The Habitation Control Centre, an earth space station analogue test site (external to the facility) and an EVA terrain hall (internal to the facility) and an area for public outreach.

The context of the FLaSH preliminary study is placed at Phase 1 of the roadmap presented in Figure 1-2 (Evolution phase-I). The FLaSH preliminary study focused in the design of the Habitat Module Complex (HCM), ensuring that the design supported modularity for system and technology exchange within the facility. Besides, defined a preliminary configuration for LSS close-loop operation. Beyond that, mass budgets within the systems were computed to track material closure of the habitat. Human factors and long term isolation investigations results from previous studies were also considered. The study did not addressed mass and power restrictions. This is a very unusual situation because the studies carried within the DLR's Concurrent Engineering Facility usually involve space driven missions where mass and power are relevant cost drivers.

The objectives definition according to the FLaSH preliminary study are presented in Table 3-1:

Table 3-1: FLaSH's mission objectives [14].

Mission Objective	Mission Objective Description
1	Testing the concept of a fully self-reliant artificial human habitat
2	Simulation of planetary exploration missions
3	Testing and qualification of different innovative technologies for systems and modules for space and terrestrial application
4	Public outreach for exploration and urban application

The study focused and put special emphasis on the mission objective number 3 since it is the more relevant objective considering the Evolution 1 step of the roadmap presented in Figure 1-2 of chapter 1.The FLaSH standard requirements are presented in Table 3-2. The requirements 9, 10, 11 were considered as the major requirements in order to ensure that the facility presents a configuration that leads and promotes an easy exchange of systems and subsystems between modules.

Considering the information presented through the mission objectives and requirements it is possible to elaborate a table presenting the FLaSH's LSS design main drivers, as defined and listed in Table 2-1. The crew size and the mission duration drivers are specified in the requirements 1 and 2. The cabin leakage is derived from requirement 3 where it is specified that the facility must achieve a total of 95 % of closure. The resupply capabilities have been defined as once per year since the facility is meant to operate as a closed-system, i.e. with minimum amount of resupplies, although it is Earth-based and accessible all year.

Table 3-2: FLaSH 's Requirements [14].

Requirement	Global Requirement Description
1	The HMC has to accommodate 8 permanent residents for a time period of at least 1 year.
2	The HMC has to accommodate up to 4 additional short-term residents for a maximum time period of 2 weeks, 4 times a year.
3	Closed cycle loop of up to 95% shall be applied for all habitat loops, unless specified otherwise. The remaining 5% of supplies are to be gained by ISRU utilization.
4	Consumer products (up to 90%) and machinery components (up to 30%) shall be produced within the habitat system.
5	The HMC lifetime shall be a minimum of 20 years
6	HMC and HCC shall be connected by a walkway with an air lock.
7	A public engagement area shall be implemented for the FLaSH infrastructure for education and public outreach; public visibility shall be enhanced by visitor accommodations/infrastructure.
8	Each module's dimensions shall not exceed 6 m x 6 m x 10 m (Height x Wide x Long).
9	Modularity shall be enabled for easy exchange of systems and subsystem of one functional module, i.e. a standard module design has to be implemented.
10	Small repairs and minor subsystem exchanges shall be executed during habitat test runs.
11	Major (sub) system changes shall be implemented during phases of non-operation of the facility, before test campaigns.
12	Efficient accessibility (from in- and outside) of each subsystem/ module shall be ensured by an endurable infrastructure.
13	The overall area occupied by FLaSH shall not exceed an envelope of 60 m x 100 m.
14	The exercise of EVA shall be simulated within the overall FLaSH infrastructure.

Table 3-3: LSS's mission drivers for FLaSH based on the 2012 preliminary study values.

Mission Characteristics	Value	Justification
Crew size [CM]	8 +4 (2 weeks)	Requirement 1 and 2
Mission duration [years]	1	Requirement 1
Cabin leakage [%]	5	Requirement 3
Resupply capability	Once per year	Mission objective 1 and Requirement 2
Power availability	No power restriction	Preliminary study assumption #3
Pressurized volume [m^3]	360 x 11 m^3 (modules)+ 540 m^3 (dome)	Requirement 8
Gravity	Terrestrial	The facility is intended to be on earth
Contaminant resources	Variable	High variability since is intended to test the interoperability of some LSS
Using- In Situ resources	Yes	Requirement 3

The volume availability is restricted to the HMC and dome volume capability that will accommodate all the LSS and the crew. Since the dome will be under closed-loop conditions it is considered as pressurized volume. As stated in chapter 2, floor area is a more suitable measure unit for Earth-based facilities.The FLaSH will provided a total of 444,75 m^2 per crewmember, (considering a crew size of 8 members and including the dome area). The contaminant resources have been set as variable. Depending on the technologies used, the by-products of the processes carried out will vary the amount contaminant resources. Since the facility will operate under a 95% of closure, the ISRU module is in charge of providing the 5 % as specified in Requirement 3.

3.1 Habitation Module Complex

The Habitation Module Complex (HMC) will be the most important element of the infrastructure for the current work since it will accommodate all the functions and technologies dedicated to ensure a self-reliant human habitat. The HMC configuration consists in 12 modules, connected between them through a passage, placed following a circular pattern around the dome volume, Figure 3-2. The preliminary study concluded that the selected configuration fulfills properly the major requirement 9.

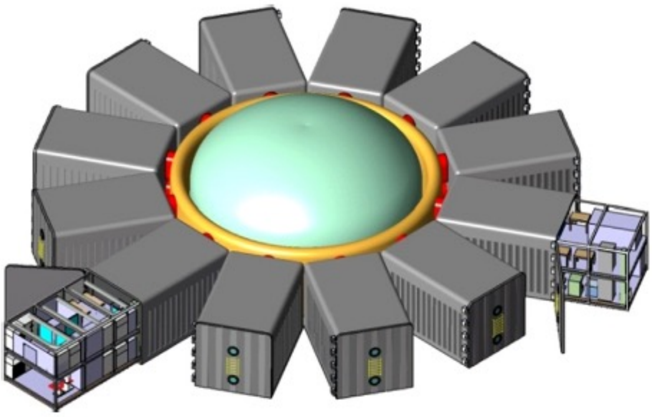

Figure 3-2: Habitation module complex (HMC) general configuration [14].

Each functional module has an external layer acting as a shell, isolating the module from the exterior. The internal layer of the module is structurally designed to carry loads and sound damping covers are available in order to reduce noise levels. The standard version of the modules' interior has a two floors configuration, except the living module, which is divided in three floors in order to accommodate and provide a suitable habitation space capable of separating group and private activities. The inner layer will also accommodate the system, subsystems and equipment for carrying out the tasks assigned to the module. Besides, will provide the space required by the crew in order to carry up maintenance, operation and research tasks within each module. Since each module is accessed through a one-piece heavy door, porthole hatches were added (the number varies in function of the number of levels of each module) in order to allow the crew escaping in case of an emergency situation. The modules are interconnected through two pressure looks.

Figure 3-3: Generic Layout Configuration of the HMC modules [14].

In Table 3-4 is possible to find a description of each functional module within the HMC

Table 3-4: HMC Modules and description [72] [14].

Module ID	Description
Air	Dedicated to research and development in atmosphere regeneration technologies. This module must ensure a breathable atmosphere for the crew and will explore bioregenerative as well as physicochemical technologies.
Water	The water module ensures that crew water requirements are covered. Besides, it grants that each module has access to usable and water. The module will address research on water storage, treatment and purification. Within the preliminary analysis a total of 6 water types were defined: *potable water,* grey *water*, yellow *water, green water, evaporation water, and waste liquid.*
Waste	Dedicated to technology research waste collection, recycling and storing. The module will consider both types of waste: organic and inorganic. In the current FLaSH's configuration it will also accommodate the laundry system for the crew.
Greenhouse	Dedicated to research on Controlled Environment Agriculture (CEA) technologies, soil types as well as soilless cultivation for supporting fresh food supplies for the crew and atmosphere regeneration, with specific functions as CO_2 reduction and O_2 generation. Besides, can be used for research on organic waste reduction and regeneration in collaboration with the Waste module
Animal	Dedicated to research on the possibilities of an animal husbandry for the required fresh food protein supply to the inhabitants. Advanced and fish farming techniques are considered as well as isolated LSS for the different organisms involved.
Food Processing	System research in technologies capable of refining raw resources from the greenhouse and animal module and convert them into a ready to eat food (e.g. from wheat to pasta). Storage and food management systems will also be investigated.
Living	The living module aims to host 6 to 8 permanent inhabitants for a period of one year and 4 visitants for a maximum stay of two weeks, 4 times a year. It considers and supports all the necessary activities for human beings involved in long –term missions.
Sickbay	A self-reliant medical station prepared to treat any medical condition that could be developed during long duration missions. Therefore, it will be equipped for the treatment of minor as well as major injuries, including injuries demanding on-site surgery. It will enclose two spaces: one for medical treatment and another for isolation in case of infectious diseases.
ISRU	Dedicated to research on technologies for propellant and life support consumables production from in situ materials. Initially, the module will takes into consideration ISRU technologies for both types of environment: lunar and Martian.

Module ID	Description
Workshop	The workshop module will be used for manufacturing, repairing electronic and mechanical parts. The materials employed for that purposes are either obtained from recycled plastic or metals from the waste module or raw material from the ISRU Module.
Energy Modules	This module will investigate technologies for energy production, harvesting and regeneration to fulfill the power requirements of the other modules. The functionalities and requirements were not addressed in the 2012 FLasH's preliminary study.
Spare Module	This module is meant to include redundant (sub)system and technologies in case of breakdown of any of the other modules.

3.2 *Fluxes balances within the facility*

In order to document and screening the material closure levels of the facility in a quantitative manner the 2012 study also determined the material fluxes between the different FLaSH's subsystems by using an excel-sheet named as the "habitat matrix". The habitat matrix summarizes all the material flows between all subsystems. In Figure 3-4 is presented an excerpt. The left column denotes the compounds/ material flux within the facility. The second column provides the final amount of the specific compound / material flux, i.e. the sum of the total demand (yellow) and supply (green) of that compound within the facility.

Parameter Demand	Sum	Air Module	Animal Module	Food Processing Facility	Greenhouse Module	ISRU Module	Living Module	Sickbay	Waste Module	Water Module	Workshop Module
total anorganic solid waste	454,00	0	0	0	0	454	0	0	-1,79	0	1,79
total Ar	0,08	0	0	0	0	0,08	0	0	0	0	0
total C6H12O6	0,01	41,30	-6,45	-34,84	0	0	0	0	0	0	0
total CH4	1,81	0	0	0	0	1,81	0	0	3,45	-3,45	0
total CO	6,37	0	0	0	0	6,37	0	0	0	0	0
total CO2	4,76	-60,58	52,1	0,6	-16,45	4,76	8	0	5,544	10,8	-0,01
total drinking water	-87,02	-24,78	-960,48	-50	557,71	17,15	-153,6	0	-23	559,98	-10
total Evaporated Water	2,05	-28,10	8,5	6,8	0	0	14,45	0	0	0,4	0
total fertilizer	0,00	0	0	0	-46	0	0	0	46	0	0
total food	0,55	0	2,35	-28,15	26,35	0	0	0	0	0	0
total green water	-1,00	0	720	0	-720	0	0	0	0	-1	0
total grey water	-3,73	28,10	240	43,2	123,81	0	58,72	0	51,92	-554,48	5
total H2	-1,11	0	0	0	0	-1,12	0	0	0,01	0	0
total liquid waste	0,00	0	0	0	0	0	60	0	-60	-5	5
total Mars atmosphere	-20,00	0	0	0	0	-20	0	0	0	0	0
total Mars soil	-105,00	0	0	0	0	-105	0	0	0	0	0
total N2	0,10	0	0	0	0	0,1	0	0	0	0	0
total O2	33,60	44,06	-34,4	0	11,96	36,82	-6,56	0	-2,584	-15	-0,70
total oil/brine	0,50	0	0	0	0	0	0	0	0	0,5	0
total organic solid waste	0,01	0	-92,92	33,5	57,63	0	1,8	0	0	0	0
total raw materials	5,00	0	0	0	0	5	0	0	0	0	0
total regolith	-405,00	0	0	0	0	-405	0	0	0	0	0
total trace gas	0,00	0	-5,00	0	5,00	0	0	0	0	0	0
total yellow water	0,00	0	0	0	0	0	12,92	0	-12,92	0	0

Figure 3-4: Habitat Module Matrix. Representation of the material fluxes' mass in kg/day. Green cells and positive numbers refer to supplies, yellow cells and negative numbers refers to demands, blue cells means balanced material fluxes [14].

The rest of the columns indicate the demand (yellow) or provision (green) of each compound in every module / subsystem. Ideally for a closed-loop facility the flux sum should be zero (except for the regolith and Mars soil). In the habitat matrix can be observed that several fluxes values diverge from the zero value, including overproduction (oxygen, inorganic waste) as well as scarcity (drinking water) being necessary further iterations of the design to find balances. For certain compounds, as in the regolith and Mars soil, the total sum is expected to be less than 0. This is due to these compounds are used as a material input to the facility in order to compensate for the 5% loss on closure degree from leakage.

A detailed explanation about how FLaSH will operate in order to address the dual approach of Earth and Space closed loop technology development it is provided in Appendix D FLaSH operation.

3.3 Conclusions

This chapter has introduced the FLaSH's preliminary configuration as a result of the study carried in 2012 at the DLR's CEF. The FLaSH's core element is the Habitation Module Complex (HMC). The HMC is integrated by 12 modules each one of them addressing a specific domain necessary in order to achieve a self-reliant human habitat. The modules are: Air, Water, Waste, Greenhouse, Food, Animal, Living, Sickbay, Workshop, ISRU, Energy and a spare module. The spare module will be used for allocating redundant technologies in case of failure of any other technology avoiding to interrupt the closed-loop operation test run.

Furthermore, from the review of the 2012 study have been possible to obtain the FLaSH's main mission drivers with impact on the LSS's design, see Table 3-3. In comparison to the other facilities studied in chapter 2, Table 2-5, the FLaSH will be an Earth-based facility. Its ambitious goal of attaining a 95% of material closure places it as an infrastructure similar to CELSS since they operate with the highest closure index. However, in contrast to CELSS, FLaSH will consider the three types of technological solutions for regenerative functions: regenerative and non-regenerative physicochemical technologies as well as bioregenerative technologies.

The benefits of including all type of technologies are not limited to the increase in the FLaSH's opportunities for technology testing. As stated in chapter 2, physicochemical regenerative technologies are the best candidates for LSS in mission durations lower than 5 years. Besides, non-regenerative physicochemical technologies are the most reliable technologies, a characteristic that place them as the best candidates for emergency scenarios. Therefore, in long-term spaceflight it will become very important to understand and predict how all these technologies interact, in all possible scenarios: standard and emergency operation.

Furthermore, FLaSH's mission requirement 11, in combination with requirement 9, seeks to incorporate a feature in FLaSH that has not been detected in the other LSS infrastructures studied. As defined in Table 3-2:

- Requirement 11 states that: *"Small repairs and minor subsystem exchanges shall be executed during habitat test runs."*

- Requirement 9 states that: *"Modularity shall be enabled for easy exchange of systems and subsystem of one functional module, i.e. a standard module design has to be implemented*."

Small repairs are considered as maintenance work and have been reported in other infrastructures such as Biosphere 2 or BIOS III. However, none of the studied infrastructures addressed the modularity for easy exchange of systems and subsystems as well as the possibility of minor subsystem exchange during the habitat test runs. The disadvantage of rigid an preset configurations resides in the necessity of stopping the test-campaign in case or malfunction of a subsystem followed by long redesign periods until the facility is operational again.

According to the review, FLaSH will be the only facility including and In Situ Resource Utilization module for studying the creation of LSS consumables from planetary (Moon and Mars) resources. This module is of high relevance for achieving a completely self-reliant habitat.

Finally, the FLaSH dual approach of developing technologies for terrestrial and space application has been only noticed within Closed Ecologically Life Support Systems (CELSS), intending the study of biosphere processes in order to be implemented at small scale Earth alike LSS. However, as previously mentioned CELSS are limited to the used of bioregenerative technologies for the regenerative functions.

4 FLaSH Modules functionalities and technological options

The most advantageous feature identified in the FLaSH is, in contrast to previous attempts of closed-cycle habitation, its modular configuration, allowing technology and subsystem exchanging while being operational with different systems (depending on clear interface definitions). FLaSH will allow exchange of components and maturation of technology, not making technology maturity a condition for usage.

For that reason it is important to identify the functions involved in FLaSH and as many as possible technologies capable of performing LSS functions. This information can be used in further studies as a database of technologies and functions involved in LSS infrastructures. Furthermore, the modules' functionalities and the technologies identified will provide the information to identify the universe of study for the research opportunity.

Recalling the overall aim of this thesis, this chapter addresses the *review and studies the current FLaSH configuration and identify potential candidate technologies.*

4.1 Methodology.

During the FLaSH preliminary study identified the main functions carried within each module of the Habitation Module Complex (HMC) .The functions identification process was performed with the support of the literature research carried in Chapter 2 and the 2012 FLaSH's preliminary study. The review on the FLaSH's preliminary study identified 48 functions carried out within the HMC. Additionally, this thesis contributed to the classification of the identified functions in regenerative or non-regenerative functions.

Anticipating that several technologies could be used to perform those functions, the ESA Technology Tree (it is explained in detail in the next section) was employed in order to rely on systematic classification framework. Besides, other significant information regarding the technology classification was also collected and presented as the regeneration capacity, the process in which it is based (i.e. biological or physicochemical) and if it was already identified and proposed in the preliminary FLaSH study or was identified by the author.

Due to the fact that the candidate technologies identification process relies entirely on the available literature research [5], [6], [73], [74], [18], [24], [75], [76], [77], [23], [68], [42] [78].

4.1.1 ESA Technology Tree

To provide a systematic classification of the technologies the ESA technological tree has been used, see Figure 4-1. The ESA technological tree is a tool developed by ESA to provide a harmonized classification framework and to smooth communication in regard to technological aspects.

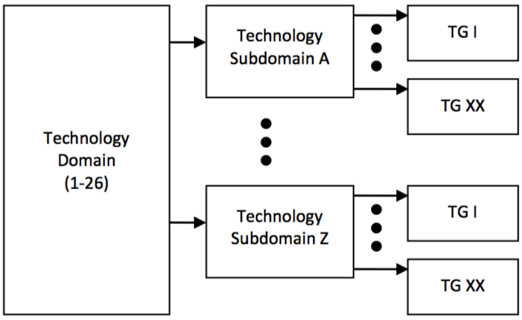

Figure 4-1: generic structure of ESA technology tree. [73]

The ESA Technological Tree is a three-level structure classification system. The first level includes 26 Technology Domains (TD) that are subsequently divided into Technology Subdomains (TsD). The Technology Subdomains are thoroughly subdivided into Technology Groups (TG).

Amongst the 26 domains of the classification system, the TD 22 is the domain of interest for this work, which includes 2 TsDs:

- TsD A: Environmental Controlled Life Support Systems (ECLSS)
- TsD B: In- Situ Resources Reutilization (ISRU), see Figure 4-2. Nevertheless, there are synergies with other technology domains in the ESA Technology Tree, e.g. “Physical and Life Sciences” (Technology Domain 14), “Structures” (Technology Domain 20) and specifically the group H “Crew Habitation and Safe Heaven and EVA suits” [73].

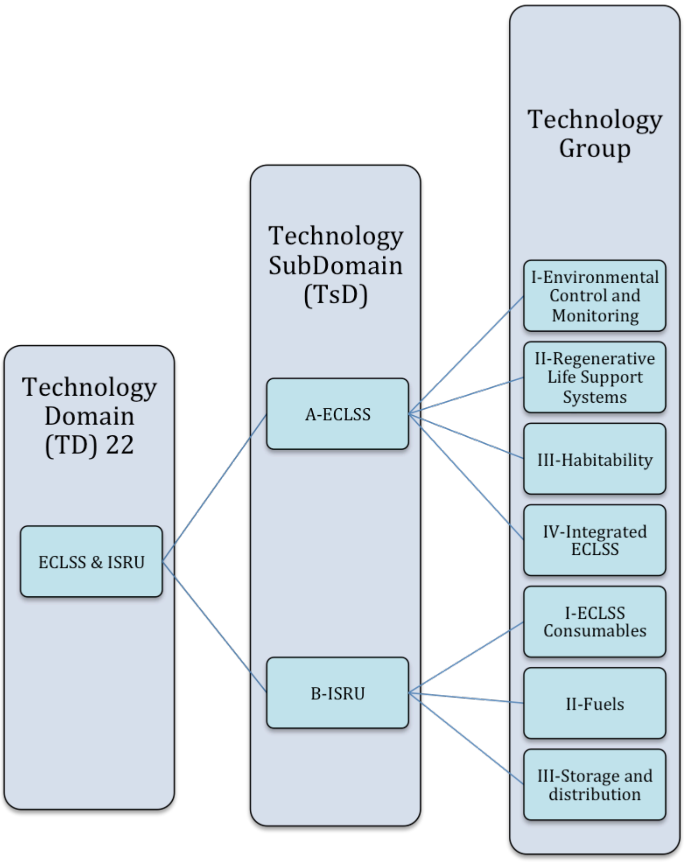

Figure 4-2 : Schematic representation of the Technological Domain (TD) number 22 [73].

The TGs of the ECLSS technology subdomain are:

- I- Environmental Control & Monitoring: technologies dedicated to air, water and food quality control and monitoring in terms of microbial and chemical contaminants.
- II-Regenerative Life Support Systems: covers all technologies related to air revitalization, water and waste reclamation as well as food preparation and production by means of P/C and biological processes.
- III- Habitability: covers all the technologies employed for the design and implementation of a human habitat, aiming for crew wellbeing, motivation and optimal performance, including definition of key psychological factors.
- IV- Integrated ECLSS covers all associated aspects and associated technologies for integrated human habitats and life support systems, including ground based test-beds and overall simulation tools and methods.

The TGs of the ISRU technology subdomain are:

- ECLSS consumables: covers all technologies for collecting and processing fluids and gases to be used as consumables for the ECLSS in human habitats.
- Fuels: covers all technologies for collecting and processing fluids and gasses to be used as consumables for propulsion and energy production.

- Storage and distribution: covers all technologies for fluids and gasses storage and distribution.

4.1.2 Technology process and regeneration capability

The ESA technological tree technology domain number 22 addresses the classification of the technologies regarding if are used for regenerative functions. This can be confirmed in the Technology Subdomain A, Technology Group II, see Figure 4-2. However, it does not specify whether if the technology is itself regenerative or non regenerative.

In regard to the regeneration capability, the technology will be classified as:

- *Regenerative, a* technology involved in a LSS regenerative function addressing resource reclamation.
- *Non-regenerative,* a technology involved in a LSS regenerative function with no resource reclamation.
- *Non-applicable (N/A)*, in the case of technologies performing non-regenerative functions, the distinction between regenerative or non-regenerative does not apply.

As stated in Chapter 2, considering mission duration higher than 2 weeks, regenerative technologies must prevail over non-regenerative technologies. On the other hand, non-regenerative technologies have lower complexity and higher reliability making them suitable for emergency situations. The lithium hydroxide cartridges are an example of non-regenerative technologies onboard the ISS as emergency / back-up technologies for CO_2 removal [77,78]. Since it will be necessary to evaluate their impact in the facility and their interaction with the rest of technologies they were also included in the technological study. Furthermore, pondering that the facility seeks for research and development of technologies for Space and Earth applications, involving technology transfers between both environments, it is important to include the non-regenerative technologies. These technologies are not suitable as main LSS for long duration human spaceflight but could present benefits when used for terrestrial purposes. Additionally, technologies are classified according to their physicochemical and biological nature.

4.1.3 Current technologies and candidate potential technologies

In order to ease differentiation between the technologies that were already considered in the 2012 FLaSH's preliminary study and the technologies that were identified as a result of the author research contribution, the technologies were categorized as follows:

Current technology: term employed for designating a technology that was already included and suggested in the 2012 preliminary FLaSH's study. The sources accessed are based on the FLaSH preliminary study report.

*Candidate technolog*y: term to indicate a new technology identified by the author. The sources employed for identification of new technologies are included in chapter 2 and have been outlined at the beginning of this section.

4.1.4 Limitations

The major limitation encountered in this work is the fact that the identification of new technologies has been focused on space driven technologies, therefore appealing terrestrial technological option might have been disregarded. This limitation must be addressed in forthcoming studies.

Added limitations of the study include the assumptions and specifications regarding the functions identification and technological study of the facility, namely:

- *Assumption #1:* technologies' mass are not considered
  - *Justification:* Despite for space missions the mass is a critical parameter and a mission driver, for the FLaSH no mass requirements are applied at this stage where the objective of the study is to know which technologies could be applied.

- *Assumption #2:* technologies' power is not considered.
  - *Justification*: Despite for space missions the power is as well a critical parameter and a mission driver, at this stage of the project no power requirements are applied. In future studies addressing the energy module, power requirements must be taken into consideration.

4.2 Results: current FLaSH configuration and candidate potential technologies.

This section presents the identified functions in each module, the current technologies and the candidate technologies identified by the author, classified under the ESA technology tree.

4.2.1 Air module.

Within the Air module 8 main functions were identified and 14 technologies (2 biological and 12 physicochemical processes) were accounted as current technologies, i.e. they were already included in the FLaSH's preliminary study. A total of 41 candidate technologies were identified as an author contribution. All of them were based in physicochemical processes, being 3 non-regenerative technologies, see Table 4-1.

It must be remarked that the introduction of plants for atmosphere regeneration purposes will create a source of additional contaminants. Furthermore, for TCC functions, the divergences between biological and human tolerances to contaminants must be taken into account. Any mission with duration longer than 2 weeks must consider regenerative CO_2 removal and reduction technologies [24].

Regarding CO_2 removal regenerative physicochemical technologies adsorption options (molecular sieves, osmotic membranes) are more suitable than absorption ones (amines, electro active carriers, Ion- exchange electro dialysis, carbonates, metal-oxides), because they are less expose to corrosion and degradation given the fact that adsorption methods do not undergo chemical reactions. As for the reduction methods, Sabatier system offers a better performance than the Bosch system in terms of hardware volume, mass and cycle time (i.e. time of reduction). However in terms of mass recovery the Sabatier has the lowest performance. The CO_2 electrolysis provides good performances in terms of mass, volume, and mass recovery but at expenses of increased cycle times and higher operation temperature, 871º C, compared to the 593 º C of the Sabatier.

Table 4-1: Air module. Functions identified, classification sequence according to the ESA Technology Tree, regenerative nature, process type, technologies considered in the FLaSH's preliminary study and candidate technologies identified by the author.

Functions	TsD	TG	Regeneration	Process	Current technologies	Candidate technologies
O_2 Provision	A	II	Regenerative	Biological	-Algae Reactor	-
					-Higher plants	-
				Physico-chemical	-Solid Polymer Water Electrolysis	-CO_2 Electrolysis
					-	-Water vapor electrolysis
					-	-Static Feed Water Electrolysis
					-	-Artificial Gill
			Non-regenerative	Physicochemical	- Cryogenic Tanks	-Super-oxides
N Provision	A	II	Non-Regenerative	Physico-chemical	-Pressurized tanks	-Thermal Catalytic dissociation of Hydrazine
				Biological	-Algae reactor	-
					-Higher Plants	-
					-Two Bed Molecular Sieve	- Four bed molecular Sieve

Functions	TsD	TG	Regeneration	Process	Current technologies	Candidate technologies
					-Sabatier reactor	- Amine liquid sorbent
					-	-Amine liquid sorbent
					-	-Electrochemical CO_2 Concentrator Depolarized Cell
					-	-Air Polarized CO_2 Concentrator Cell (ADC)
CO_2 removal	A	II	Regenerative	Physico-chemical	-	-Metal-Oxides
					-	-Membranes Osmotic
					-	-Electro active carriers
					-	-Ion-Exchange electro dialysis
					-	-Bosch
					-	-CO_2 Electrolysis
					-	-Advance Carbon Reactor
						-Lithium Hydroxide
			Non-Regenerative	Physico-chemical		-Sodasorb
						-Superoxide
Temperature and Humidity Control	A	I	N.A.	Physico-chemical	- Condensing Heat Exchangers (CHX)	-
					-Activated Carbon	-Reactive plasma beds
					-	-Particulate Filters
					-	-Chemisorbant beds
					-	-Super-Critical Water Oxidation (SCWO)
					-	-Ion Trap Mass Spectrometer
					-	- Direct deposition / Fourier Transform
Trace Contaminant Control (TCC)	A	I	N.A.	Physico-chemical	-	-Ion Mobility spectrometer
					-	-Thermal conductivity detector
					-	-Superoxide
					-	-Ion field effect transistors
				Biological	-	-Plants
					-	-Bacteria
Particulate Removal	A	I	N.A	Physico-chemical	-	- Particulate filter
Atmosphere circulation pressure control	A	I	N.A.	Physico-chemical	- Fans	- Valves
					- Water spry head	- N_2 fire suppression
					- Smoke charger	- Halon fire suppression

Functions	TsD	TG	Regeneration	Process	Current technologies	Candidate technologies
Fire suppression	A	I	N.A.	Physico-chemical	-	-UV/IR
					-	-Thermal sensor
					-	-CO_2 suppression fire

4.2.2 Water module.

For the Water module a total of 7 functions and 15 current technologies were identified (4 biological regenerative and 11 regenerative physicochemical) as defined in the preliminary study. A total of 27 candidate technologies were suggested through the bibliographic review, as listed in Table 4-2. Almost all the candidate technologies are based on regenerative physicochemical processes except the water collection from plant transpiration, a bioregenerative technology, and 1 non-regenerative technology. Super-critical Water Oxidation (SCWO) was considered in the FLaSH's preliminary design but was discarded due to critical problems with corrosion. Nevertheless, considering that the goal in this section is to find as many applicable technologies as possible (will increase the research opportunities) SCWO has been included.

Table 4-2: Water module. Functions identified, classification sequence according to the ESA Technology Tree, regenerative nature, process type, technologies considered in the FLaSH's preliminary study and candidate technologies identified by the author.

Functions	TsD	TG	Regeneration	Process	Current technologies	Candidate technologies
H_2O Provision	A	II	Regenerative	Biological	-	- Transpiration from higher plants
				Physicochemical	- Sabatier	- Water Vapor Electrolysis
					-	- Atmospheric Water Generator (AWG)
			Non-Regenerative	Physicochemical	- Storage tanks	-
Potable water treatment	A	II	Regenerative	Physicochemical	-Puralytics	- Re-generable microbial check valve
					-Pasteurization	-Iodine removal beds
					-	-Ultrafiltration /Reverse Osmosis
					-	-Forward osmosis
					-	- MiliQ absorption beds
					-	-Low Temperature Aqueous Phase Catalytic Oxidation system (APCOS)
					-Puralytics	- Hydrophobic ceramic membrane

Functions	TsD	TG	Regeneration	Process	Current technologies	Candidate technologies
Grey Water Treatment (Hygiene water)	A	II	Regenerative	Physicochemical	-Plasma reaction chamber	Low Temperature Aqueous Phase Catalytic Oxidation system (APCOS)
					-	-Electro dialysis
					-	-Ultrafiltration /reverse osmosis
					-	- Supercritical Wet Oxidation (SCWO)
					-	-Inductively fluidized bed reactor
Urine treatment	A	II	Regenerative	Biological	-C.R.O.P	
				Physicochemical	-	- Vapor Phase Catalytic Ammonia Removal (VAPCAR)
					-	-Vapor Compressor Distillation
					-	-Thermoelectric Integrated Membrane Evaporation Systems (TIMES)
					-	-Air Evaporation System (AES)
Wastewater Treatment	A	II	Regenerative	Biological	-Pasteurizer	- Aerobic Bioreactor
					-Aquamost	-
					-Active Chemostat Treatment	-
				Physicochemical	-Aquapure	-Quartz reactor
Water monitoring	A	I	N/A	Physicochemical	-Flow cytometer	- Electric nose
			.		-Gas chromatograph	- Ion specific electrodes
					-Atomic absorption spectrograph	-Active reaction nanomaterial
					-	-Total organic carbon analyzer
					-	-Conductivity analyzer
					-	- PH test kits
Water distribution	A	I	N/A	Physicochemical	-Pumps and valves	

4.2.3 Waste module.

For the Waste module 5 functions and 7 current technologies (2 based on biological process and 5 physicochemical) were identified. A total of 16 candidate technologies have been proposed by the author, almost all of them based in physicochemical processes with the exception of two: the anaerobic and aerobic reactors, see Table 4-3.

Table 4-3: Waste module. Functions identified, classification sequence according to the ESA Technology Tree, regenerative nature, process type, technologies considered in the FLaSH's preliminary study and candidate technologies identified by the author.

Functions	TsD	TG	Regeneration	Process	Current technologies	Candidate technologies
Waste Collection and Separation	A	I	N/A	Physicochemical	- Magnetic sort of non-organic waste	- Color recognition
					- Separator of organic /non-organic waste	- Near Infrared
					-	-X-ray transmission
					-	- Magnetic sensor
					-	-Visual spectrometry
Solid organic waste treatment	A	II	Regenerative	Biological	-Vermicomposting	- Anaerobic bioreactor
					-Combined regenerative organic food production	-Aerobic bioreactor
				Physicochemical	-Bach incineration	- Supercritical wet oxidation
					-	- Water oxidation
					-	-Dry incineration
					-	-Plasma arc oxidation
					-	-Gasification
					-	-Electrochemical incineration
					-	-Plasma arc oxidation
Non-organic waste reduction	A	II	Non-regenerative	Physicochemical	-Shredding machine	-Electric melting
Laundry	A	I	N/A	Physicochemical	-	-Waterless washing machine

4.2.4 Food module.

Within the Food module 5 functions and 14 technologies (3 biological process and 8 physicochemical) were already defined in the FLaSH preliminary study. This work contributed to the identification of 7 candidate technologies, almost all of them based in physicochemical processes, as presented in Table 4-4. The emergency stock will consider a 30-day supply for at least 8 "habinauts"[4]. Algae are a great source of protein, carbohydrates and fat. However, nutritionists recommend a maximum of 20 % of algae in a person's diary diet [6]. This work also contributed to the addition of a non-regenerative function within the module: food-monitoring which was not included in the 2012 FLaSH's preliminary study.

[4] Habinauts is the term used to denote the crew within FLaSH during closed-loop campaigns

Table 4-4: Food module. Functions identified, classification sequence according to the ESA Technology Tree, regenerative nature, process type, technologies considered in the FLaSH's preliminary study and candidate technologies identified by the author.

Functions	TsD	TG	Regeneration	Process	Current technologies	Candidate technologies
Food provision	A	II	Regenerative	Biological	- Greenhouse module food provision	- Algae
					- Animal protein supply from animal module	-
			Non-Regenerative	Physicochemical	- Pre-stored food[5]	-
Food processing	A	II	N/A	Physicochemical	-Addressed but not specified	- Grinding and milling
					-	-ECO system peeler
Food storage and management	A	II	N/A	Physicochemical	-Dry Storage	-
					-Refrigerator	-
					-Blast freezer	-
					-Deep freezer	-
					-Freeze dryer	-
					-Radio Frequency Identification (RFID)	-
Food preparation	A	II	N/A	Physicochemical	-Steam cookers	-
					-Microwaves	-
					-Dishwashers	-
					-Stoves and grill	-
Food monitoring	A	I	N/A	Physico-chemical	-	- Adenosine Triphosphate (surface test)
					-	- Acid phosphate testing (meat)
					-	- Alkaline phosphate tests (Milk products)
					-	- Photomultimeter

4.2.5 Animal module.

The animal module is dedicated for fresh food supply. Thus, the function Food provision was also included here. For the animal module only small living organisms with high harvesting index are of interest. The harvesting index (H_i) is defined as the ratio between the edible mass of the element (m_e) and their total mass (m_t). It must be remarked that the harvesting index is also used to evaluate food production performance of plants.

$$H_t = \frac{m_e}{m_t} \qquad \textbf{(4-1)}$$

[5] Includes: re-hydratable food, thermo stabilized food, frozen food and ionized food

The aquaculture and insect farming facilities will entail a dedicated LSS. In this module, 5 candidate technologies were identified (in this case food types), as listed in Table 4-5. Big animals like cattle, chicken or pigs have not been considered since they are not suitable for closed-loop habitats [72].

Table 4-5:Animal module. Functions identified, classification sequence according to the ESA Technology Tree, regenerative nature, process type, technologies considered in the FLaSH's preliminary study and candidate technologies identified by the author.

Functions	TsD	TG	Regeneration	Process	Current technologies	Candidate technologies
					- Shrimp	- Prawn
					- Oreochromis Mossambicus	- Catfish
Food supply	A	II	Regenerative	Biological	- Grasshoppers	-Grass carp
					- Mealworms	-Snail
				l	- Mealworms	-Silkworms
Oxygen supply	A	II	Regenerative	Physicochemical	- Water electrolysis	-

4.2.6 Greenhouse module.

The Greenhouse module has already been the scope of many studies and it is in a quite advanced design phase [75] [76]. A total of 7 functions were identified and 3 technologies were suggested as candidate technologies, listed in Table 4-6. The utilization of low reynolds Micro Aerial Vehicles (MAVs) can be beneficial for pollination purposes in Controlled Environment Agriculture [6]. As stated in chapter 2, biological systems are not well understood, they are difficult to model and based on processes, which are hard to control, thus the use of drones will provide a reliable option for pollination [77]. However, that reliance will be obtained at expenses of losses in the honey production capacity. The zeoponics are an appealing soil based agriculture method due the simpler infrastructure they required in comparison to aeroponics or hydroponics. Zeoponics use a synthetic soil based on a zeolite mineral substrate, containing the basic plant growth nutrients [78], [5]. Regarding soilless technologies, candidate technologies are: hydroponics, nutrient film, ebb and flow. In hydroponics the roots are immersed in a water solution containing nutrients and are aerated by pumping oxygen into the water solution. Other two well known- methods are the nutrient film and ebb and flow. In the nutrient film the root tank is smaller and contains a gentle sloop. In that case the water is pumped from the top of the tank and flows down the slope into a water tank. The ebb and the flow are tidal systems. The water is pumped from the solution tank into the root tank, then drained and pumped again as needed. This last system also requires aeration system [79].

Table 4-6: Greenhouse module. Functions identified, classification sequence according to the ESA Technology Tree, regenerative nature, process type, technologies considered in the FLaSH's preliminary study and candidate technologies identified by the author.

Functions	TsD	TG	Regeneration	Process	Current technology	Candidate technology
Agriculture	A	II	Regenerative	Biological	- Bee pollination	-
				Physicochemical	- Aeroponics	- Zeoponics
					- Hydroponics	- Nutrient film
			Non-Regenerative	Physicochemical		-Low Reynolds MAVs
Food production	A	II	Regenerative	Biological	- Carrots, snap-beans, potatoes, lettuce, onions, rice, spinach, sweet potato, wheat, peanut, soybean, apple, tomato, herbs	-
O_2 generation	A	II	Regenerative	Biological	- Higher plants	-
CO_2 removal and reduction	A	II	Regenerative	Biological	- Higher plants	-
Waste treatment	A	II	Regenerative	Biological	- Higher plants	-
H_2O generation	A	II	Regenerative	Biological	- Plant H_2O exuded	-

Considering the functions identified can be concluded that the Greenhouse module involves LSS functions related to other modules as air regeneration, waste reduction, water production and food production, in addition to present a great countermeasure for psychological problems derived from human isolation [14].

4.2.7 Sickbay module.

The study identified 2 main functions within the Sickbay module and 9 current technologies. The functions belonged to the TG III (Habitability) therefore, was expected that none of the functions is regenerative neither can be carried by biological technologies. The current work identified a total of 11 potential technologies.

Table 4-7: Sickbay module. Functions identified, classification sequence according to the ESA Technology Tree, regenerative nature, process type, technologies considered in the FLaSH's preliminary study and candidate technologies identified by the author.

Functions	TsD	TG	Regeneration	Process	Current technologies	Candidate technologies
					- X-Ray examinations	- Health maintenance computer
					-	- Blood oxymeter

Functions	TsD	TG	Regeneration	Process	Current technologies	Candidate technologies
Health monitoring diagnostics	A	III	N/A	Physicochemical	-	- Ultrasound
					-	- Electrocardiogram
					-	- Blood pressure kit
					-	- Hematology kit
					-	- Urinalysis kit
					-	- Microbiological kit
Disease treatment	A	III	N/A	Physicochemical	-Orthopedics	- Defibrillator
					-Obstetrics and gynecology	- Hyperbaric treatment facility
			-		-Obstetrics and gynecology	- Intravenous kit
					-Dentistry	-
					-Tele-surgery	-
					-Blood bank	-
					-Pharmacy kit	-
					-Therapeutic kit	-

4.2.8 ISRU module.

A total of 5 functions were identified involving 10 current technologies. Only 1 candidate technology was suggested. As seen in Table 4-8, the regenerative capability of technologies performing resource reclamation from the lunar regolith or Mars atmosphere is classified as non-applicable. This is because those technologies are not recycling resources previously contained within the habitat. It is important to remark that the artificial gill is a very innovative technology and neither evidences nor results on its performance have been reported. The artificial gill purpose is to obtain oxygen from the Martian atmosphere [6].

Table 4-8: ISRU module. Functions identified, classification sequence according to the ESA Technological Tree, regenerative nature, process type, technologies considered in the FLaSH's preliminary study and candidate technologies identified by the author.

Functions	TsD	TG	Regeneration	Process	Current technologies	Candidate technologies
Storage	B	III	N/A	Physicochemical	- Storage room	-
Oxygen provision from lunar regolith	B	I	N/A	Physicochemical	- Illmenite glass reduction	-
	B	I			- Pyrolisis / Vapor phase reduction	-
					- Carbo-thermal reduction	-
Volatiles extraction from lunar regolith	B	I	N/A	Physicochemical	- Solar wind implanted particles water processing	-
					-Sabatier process	- Artificial gill

Functions	TsD	TG	Regeneration	Process	Current technologies	Candidate technologies
Oxygen extraction from Mars alike atmosphere	B	I	N/A	Physicochemical	-Reverse water shift with H_2	-
					-Solid oxide electrolysis	-
Volatiles processing	B	I	N/A	Physicochemical	-Water processing from subsoil	-
					-Gas extraction from atmosphere	-

4.2.9 Workshop module.

The study identified 3 main functions within the Workshop Module, and established technologies were approached but not specified. This thesis fills that gap by suggesting advanced manufacturing technologies that can be used for generating new parts or repairing old ones, and can be used for electronic spare parts as well as for mechanical ones. Furthermore some of the manufacturing techniques as the EB-F[3] and Selective Laser Melting require CO_2 atmospheres for increased accuracy, thus being able to be used a sink for the CO_2 that could not be reduced [80].

Table 4-9: Workshop module. Functions identified, classification sequence according to the ESA Technological Tree, regenerative nature, process type, technologies considered in the FLaSH's preliminary study and candidate technologies identified by the author.

Functions	TsD	TG	Regeneration	Process	Current technologies	Candidate technologies
Storage	A	III	N/A	Physicochemical	-	- Clean room
Mechanical manufacturing repairing	A	III	N/A	Physicochemical	-Reparation of electric and electronic parts	- Ultrasonic additive manufacturing (UAM)
					-Water jet cutting	- Electron Beam Free Form Fabrication (EB-F [3])
					-3D printing (for metal and ABS, PVC and PET plastics)	- Electron Beam Melting (EBM)
					-Laser cutting	- Fused Deposition Modeling (FDM)
					-	- Selective Laser Sintering (SLS)
				Physicochemical	-	- Stereo-lithography (SLA)
Cloth repairing	A	III	N/A	Physicochemical	- Cloth weaving machine	

4.2.10 Living module.

The study identified 4 main functions within the Living module, being all of them related to human factors associated to confinement and isolation aspects. All the identified and candidate technologies will belong to the Technology Group (TG) III: Habitability. That TG also covers the definition of key psychological factors and the proposed psychological counter measures are considered as technologies. Some of the psychological aspects or technologies suggested are not possible to classify into P/C or Biological technologies. The results of the review are listed in Table 4-10

Table 4-10: Living module. Functions identified, classification sequence according to the ESA Technology Tree, regenerative nature, process type, technologies considered in the FLaSH's preliminary study and candidate technologies identified by the author.

Functions	TsD	TG	Regeneration	Process	Current technologies	Candidate technologies
Psychological monitoring	A	III	N/A	N/A	- Weekly psychological support	-
			N/A	Biological	- Contact with other living organisms: plants and animals	-
Coping with isolation	A	III	N/A	N/A	- Audio/Video equipment	- Environment personalization
					- Library and art equipment	- Surprises and options
					- Fitness area	- Moderate alcohol consumption
					- Conference / communication	- Astronomical observatory
				N/A	- Contact with other living organisms: plants and animals	-
Crew and interpersonal dynamics	A	III	N/A	N/A	- Common and social areas	-
					- Private areas	-
Coping with dimensional Confinement	A	III	N/A	N/A	- Solar collector for ensuring natural light	-
					-Large free spaces within the dome	-
				N/A	-Windows at every quarter	-
			N/A		-Fitness area	-

.

4.3 Conclusions

This chapter identified a total of 41 functions, within the HMC's modules, and classified them as regenerative and non-regenerative functions or non-regeneration applicable (N/A). Regenerative functions represent the 43% of the total amount of identified functions. Regenerative functions are distributed within the Air, Water, Waste, Greenhouse, Food and Animal modules. Therefore, considering that closed-loop technologies are applicable in regenerative functions, those modules present higher opportunities for closed-loop technology applications. However, the Living, Workshop and Sickbay modules, although not employing closed-loop technologies directly, they are vital to ensure the integration of the human system within the habitat. It must be recalled from chapter 2 that the human is the main driver in LSS and without the human system there is no point in testing closed-loop technologies.

Finally, after filtering the number of candidate technologies, eliminating repeated counts of a same technology applied for different functions, can be concluded that this thesis contributed to identify a total of 110 candidate technologies, with 47 regenerative technologies.

The major limitation of this part of the work is represented by the fact that the majority of candidate technologies identified by the author belongs to the space field literature and terrestrial technologies are underrepresented. However, this limitation is not invalidating considering that all space technologies must endure tests and demonstrate capabilities in a terrestrial environment prior to be tested and utilized in space, as to ensure they can perform in both environments. Other recommended sources for identifying new technologies in future studies are patent databases, since they can contain information for innovating technologies.

5 FLaSH's research opportunity study

This chapter presents the study of the FLaSH's research opportunity. The study is based on internally generated primary data. The information was collected by means of an online survey from potential participants from European countries. Potential participants were defined as entities with areas of expertise related to any of the FLaSH modules' functionalities or technologies described and identified in chapter 4. Target entities belonged to European public bodies (e.g. agencies), industry (e.g. large, medium and small enterprises) and research organizations and academia (e.g. universities, research institutes).

Proper survey generation process involve 6 key design steps presented in Figure 5-1:

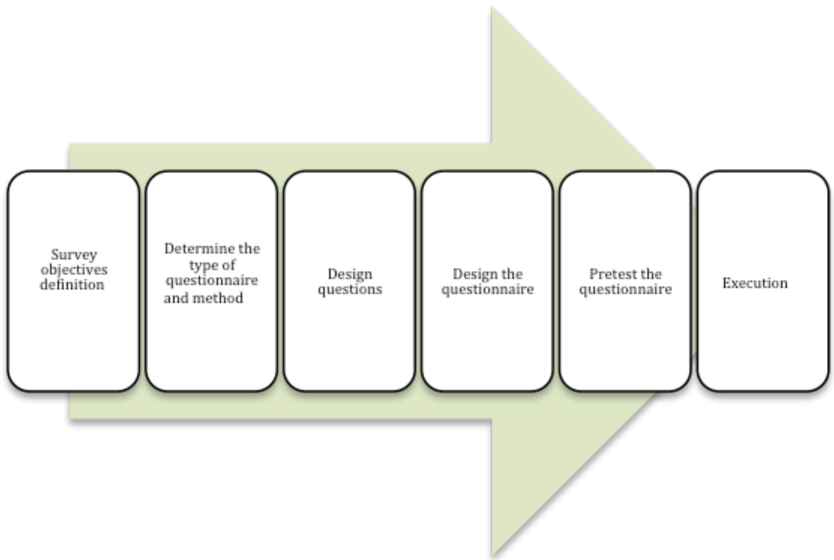

Figure 5-1: Steps for conducting a survey. Adapted from [81]

5.1 Survey objectives.

The main objective of the survey was to generate primary internal data to answer the questions of the research opportunity presented in Chapter 1, namely:

- Gather information about the type, size and nationality of the participants.
- Retrieve data about entities preferred modules, and the opportunities in the modules' technologies.
- Understand the expectations and the perception of their role in case of participation with FLaSH.

5.1.1 Sampling methodology.

The entities integrating the population of study were characterized by:

- European entities whose activities or technologies were linked to the FLaSH's modules or modules' technologies.

Considering that no prior database of this type of entities existed, the author created a directory of 172 potential participants entities evaluating their available information in order to determine their nationality and whether any of their research fields, services and technologies were connected with the FLaSH's modules domains and / or modules' technologies. This database was used as the sample of study. This sampling technique is known as the judgemental sampling. In this technique the researcher selects the elements based on judgment or expertise, considering these elements as representative of the population or appropriate. Judgmental sampling selection, as a non-probabilistic method, is an inexpensive technique. However, obtained results are not statistically projectable to the entire population of study, although may provide a relevant insight in relation to the characteristics of respondents [82]. Besides, to increase the outreach of the survey, Participants were asked to forward the survey's invitational e-mail to other participants that might be part of their network. This technique is known as the snowball sampling technique.

The final sample was constituted by 151 elements since 21 elements from the initial 172 stated that they were out of the office for holiday period, not knowing the reason to be included in the study or the entity did not exist anymore.

The accessed sources for the identification of potential participant entities were:

- ESA SMEs database: the ESA's Technology Tree, Technology Domain 22.
- CORDIS, a public repository for EU funded research projects and main results. Entities were identified as members of funded projects of the 7^{th} Framework Program in the areas of environment, food, agriculture and biotechnology, space, transportation and health.

Additionally, the process involved the utilization of the Google search engine for the identification of companies with services / technologies that could be relevant for FLaSH.

The author of the work is aware that the amount of entities in compliance with the presented criteria is significantly higher but with the time available and due to the difficulties obtaining reliable contact information was not possible to obtain more participants.

5.1.2 Questionnaire design and questions

Following the questionnaire's objectives definition and the outlining of the information that is required to obtain from the participant, the questionnaire could be designed and implemented. The questionnaire can be consulted in Appendix C: Questionnaire.

The questionnaire included a total of 22 questions. However, it must be remarked that due to the survey design features, the number of questions that participants had to answer varied from a minimum of 11 questions to a maximum of 22, depending on their specific answers. The number of questions varied because some low level questions were triggered by higher-level answers in order to obtain further information in specific topics.

The questions were grouped into three major sections according to the type of data that it was intended to collect:

1. Profile of potential participants, such as the type of entities, size, geographical distribution and their activities' sector.
2. Awareness and previous experience of the participants in any of the main LSS functions supported by the facility.
3. Participants' preferred modules and technologies.
4. Participant's perception of its own technological relevance for the FLaSH operationalization and participant's expectations in regard to the outcome of participation in FLaSH. Besides, this sections retrieve information to determine the participant's preferred method of collaboration and their vision in regard to self-reliant habitats future development.

Can be noticed that the structure of the survey differs from the specific outline in which the research opportunity questions were presented in chapter 1. This is because the questionnaire's structure was based on survey's good practices: starting with general questions and progressing to more specific ones [83]. An online questionnaire was implemented with the Limesurvey®. The survey was conducted within four weeks in August 2014.

5.1.3 Pre-test and execution

Following the survey's preliminary design, a test run was carried out internally within the Space Segment System Analysis (SARA) department. Suggestions and corrections from the members were collected and the survey was updated. Main changes involved the survey's introduction, where the FLaSH was described, and the order of questions. On August 4th the survey was forwarded to the selected sample. The data collection period finished on August 29th.

5.2 Survey results and discussion.

The survey collected 45 answers, but only 36 were considered, as 9 respondents abandoned the survey between the second and the third section. Hence the response rate achieved was 21%. It must be recalled that due to the non-probabilistic sampling method the results are not significant to the totality of the universe of study. Any analysis intending to derive conclusions for the population of interested/ non-interested participants (such as confidence intervals data retrieved from the survey) was considered biased and not carried out.

5.2.1 Survey's results: participant's profile.

Answers were collected from 15 European countries, 13 belonging to EU member states. Appendix B:Atmosphere

As mentioned the human body can stand periods up to 4 minutes without oxygen, the metabolic rate of oxygen consumption per day per man is Table 2-2. Nevertheless, the provision of oxygen is not the only need of the human body. For a breathable and comfortable atmosphere other gases are needed, known as make up gasses The total atmosphere pressure will be equal to the sum of all partial pressure of all gasses involved:

$$PB = pO_2 + pN_2 + pO_2 + pCO_2 + pH_2O + \cdots + pX_n \qquad \textbf{(8-1)}$$

Where the PB is the total barometric pressure, the prefix *p* denotes the partial pressure and O_2, N_2, CO_2 and H_2O represent the components in the atmosphere. Often, in first order approximations other gases than the O_2 and the inert gas, in this case N_2, are not considered. Therefore; reducing expression to:

$$PB = pO_2 + pN_2 \qquad \textbf{(8-2)}$$

Considering sea level conditions and the standards given by:

Reference	P [kPa]	pO_2 [kPa]	pCO_2 [kPa]
Sea level	101.3	21.3	0.04
NASA standards (max. & min.)	99.9-102.7	19.5-23.1	<0.04

Temperature and Humidity

Temperature and humidity covers the aspect of habitability regarding the climate presented in Figure 2-6. It is recommended to maintain the habitat humidity and temperature control within a comfort box with the specific values of 25-70 % of relative humidity and temperature of 18.3-26.7 °C for the total duration of the mission and excluding specific operations of duration of less than 4 hours and hatch open after landing and

Trace contaminant control

Missions of more than 30 days in closed –loop must keep track of volatile contaminants; e.g. alcohols, aldehydes, aromatic carbohydrates. For a complete list of the maximum allowance Trace Gas Contamination refer to [16].

Hygiene

The Hygiene aspect is very important not only from the physiological perspective but also from a psychological one. Personal hygiene eliminates microorganisms and avoids the spread of disease as well as increasing the comfort of the crew. From the psychological perspective grooming can enhance self-esteem, improving the morale, fact that it can lead into an increase in productivity.

Sleep

Sleep is a physiological need of the human body with impact in the overall crew comfort and performance. Studies determined that with sleeping periods below 8 hours results in a decrease of the cognitive performance of the crew. Furthermore, subjects restricted to 4 hours of sleep per day for a 14 day period show the same decrease in peak performance than a subject with continuous sleep deprivation for two days. Sleeping periods of less than 8 hours may be allowed for short lapse time.

Noise

The sound is a physical disturbance in the air. That sound regarding the human body can be whether enjoyable or undesired and annoying [18]. The latter is the disturbance defined as noise and it is known for being the source of:

- Stress problems and sleep depravation
- Lowering cognitive performances.
- Cause physical illness and permanent loss of hearing due to long period expositions.

Noise requirements will vary depending on the country and region . Considering that different nations have different legislations and considering that the audition performance it is not affected by environments of reduced gravity the NASA STD-3001 appeals to apply the regular standards on Earth.

The equivalent noise pressure level is an approach for averaging all the noise sources and their frequencies. International standards set a sound pressure level for occupational purposes of 85 dB (A) (8 hours working averaged per week) by the ISO 1999:1990. However those values do not warranty the safety of the auditory system, thus EC directives set the maximum level on 80 dB (A). The unit A stands for “weighting filter A” which is developed in order to account the effect of the variation of the human sensitiveness for the range of audible frequencies. The frequency weight filters permits to weight the contribution of a specific filter to the overall pressure level .

The equivalent noise pressure levels may never overcome the 110 dB, value at which hearing loss and damage is induced. Noise can also act as a stressor by reducing memory capabilities

Vibrations

Human sensitivity limits for vibrations are given in the ISO 2631, since the human body can be exposing to vibration for the whole body or isolated parts. The NASA STD-3000 refers different levels of vibration for non-sleep phases, sleep times, vibrations limits for performance and hand vibrations. In Figure A 1, the different vibration limits applied to the different body parts are presented:

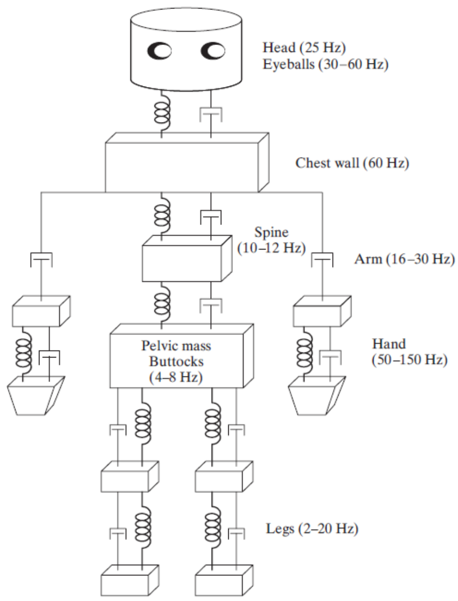

Figure A 1: Sensitivity of vibration for the different parts of the body

Lighting

Lighting needs must take into consideration tasks demands (not only intensity but also color), architectural features (prevision of shadow regions and glare) and luminance adaptation. Furthermore, lighting conditions must ensure synchronization with the wake – sleep cycles and entrainment of circadian cycle.

Circadian cycle entrainment is influenced by diverse environmental stimuli, being the exposition to bright light the most relevant .

Radiation

Radiation protection is another aspect to consider for the human health. There are different types of radiation (ionizing and non-ionizing) and regarding space flight above Earth´s radiation belts is the. Radiation limits depend on age, gender and size as well as the type of organs or tissues that are receiving the radiation: NASA requirements set radiation limits between 1 to 3 Sieverts [Sv] for a year and a maximum to 6 Sv in skin for a career time.

Acceleration

The excess as well as the lack of acceleration may have impacts on the human body. Regarding the excess of acceleration the system must limit the duration depending the magnitude and direction, see Figure A 2.

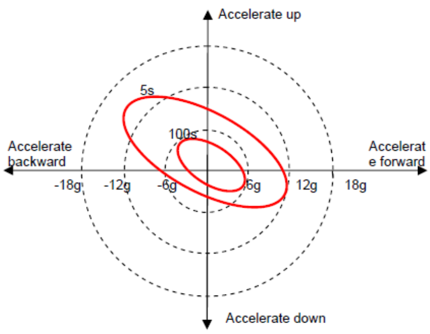

Figure A 2: Acceleration magnitude, direction and time limits.

Regarding the lack of acceleration, microgravity environments induce several physiological changes as: space motion sickness, fluid shifts, and bone demineralization, muscle atrophy, hematological and hormonal changes .

Food

The food has been previously defined as one of the critical consumables for ensuring human survivability. Nevertheless, the type of nutrients required, menu planning, and quality have a direct impact not only in the wellbeing of the crew but also in their morale. The top ten ranking of preferred food by the astronauts is provided at .

Space and interior layout

Interior space and layout main goal is to ensure the wellbeing of the human crew by providing the best space and distribution for the maximum working efficiency and comfort during the duty and off duty times. The main drivers for the interior size and layout are: mission time, number of crewmembers, gravity environment, mission objectives, stowage and mass and power mission requirements. Three terms are in use to describe the spacecraft / habitat size :

- The total pressurized volume
- The habitable volume also known as the “sand volume”. Corresponds to the resulting volume from the subtraction of the volume occupied by the lab-racks or hardware to the total pressurized volume.
- Net Habitable Volume (NHV) refers to the functional volume remaining for the crew after deployment of all equipment, stowage and all possible architectural deficiencies.

Since minimum NHV drives the design of the overall spacecraft size minimum NHV estimation is recommended during the design phase. There are two processes for calculating the NHV: the task evaluation method and the experience-based method. The task evaluation method consists in the study of the required space for all the duties and activities the crew will perform inside the habitat considering if they are suited or unsuited. The experience-based method relies on data from previous missions. The NHV presents different figures of merit depending on the gravity environment:

- Microgravity: figure of a merit in m^3. For microgravity environments the NHV is computed as a volume.
- Gravity: figure of merit in m^2. In the case of environments with gravity the NHV is computed in terms of square meters despite the name includes the term of Volume. The reason to keep the term volume is due to a minimum of 2,5 m^2 standard, depending on the gravity environment where the habitat is placed. For this particular case, the experience-based value relies on previous subaquatic habitat missions.

Living space on spacecraft’s or space habitats can be also determined with a parametric relation, known as the Celentano curves .

$$\frac{V}{CM} = A(1 - e^{-\frac{duration}{B}}) \qquad \textbf{(8-3)}$$

Where A can attain three accommodation levels: “tolerable” (A=5), “performance” (A= 10), “optimal” (A=20). The *B* is a scale factor in day units, defined as 20 days.

Finally, for long-term habitation, the habitat pressurized volume per crewmember (i.e. living volume and working volume) should not be lower 120 m^3 [24]. The manner, in which the available space could be distributed according to the activities to be carried, is known as “zooning”, addresses zooning regarding the privacy of the activities and if they are carried out collectively or individually, see Figure A 3:

Figure A 3: Activities distribution regarding privacy and team- working requirements .

Psychological aspects

An increase of the mission durations for space exploration leads to a higher impact of psychological and interpersonal factors in human crew behaviour and performance . Being those factors hard to quantify, they will be addressed in a broader manner that the rest of the human aspects. As presented in Figure **2-6**, those factors involve long duration mission aspects as: like crew schedule, crew composition, interpersonal dynamics, and communication are factors to be considered.

- **Psychiatric aspects:** Some mental health problems are more frequent during space missions and most of the reported are just adjustments reactions to external stressors: e.g. depression due to isolation in orbit. Psychosomatic problems and, to a lesser extend, psychiatric disorders, have been noticed in space analogues and submarines scenarios. That is not the case of spaceflight since potential astronauts undergo an intensive psychological screening.
- **Communications:** in a mission involving long distances no real time communication will be possible increasing the isolation factor.
- **Crew composition and interpersonal dynamics:** productivity and performance are related to the form of crew interactions and it is important to consider psychosocial issues and the crew selection. Main issues to regard are: alienation, the host-guest problem, minority status and organizational culture, psychological closing, autonomous level, and displacement and crew autonomy.
- **Schedules:** It is important to implement schedules with duty and duty-off times balance, meal periods and housekeeping activities. An unbalanced schedule can lead to irritability, stress increase and decrease in crew performance.

In order to reduce the effects of those factors different counter-measures may be applied.

Graphic support for survey respondents' profile, shows the geographical distribution of the survey's participants. One respondent does not figure in the map since she/he framed her/his entity as international. Germany and Spain represent the countries with the higher number of responses, over 5 per country. Serbia, Hungary, Switzerland, Czech Republic and Italy are the countries with the lowest number of responses accounting 1 response per country.

Regarding the type of entity, 16 answers were from industrial companies or SMEs, 16 from research organizations and academia and 4 from public entities. On one hand, the research organizations and industrial companies are principally represented by small and medium sized entities, i.e. with less than 250 employees. Indeed, 15 entities from the industrial companies and SMEs are SMEs. On the other hand, public bodies responses are majorly composed by large size entities: 3 out of 4. The lower rate of responses for public bodies is due to the lower representation they had in the sample of contacted potential participants.

Data concerning the entities' expertise area presents multidisciplinary backgrounds. The sector of *environment* obtained the highest response frequency. This sector is related to several FLaSH's modules, therefore it has a higher representation in the sample, as a result of the bias induced by the sampling method. Others high response areas are the agrofood, biotechnology and chemistry, space, materials, aeronautics and intelligent energy, see Appendix B.

5.2.2 Survey's results: participant's awareness and previous experience.

Responses revealed that 15 respondents are related with closed-loop technology, 10 with resource-reclamation technologies and 7 with human self-reliant habitats. The water regeneration (water collection, treatment and reclamation) and the waste regeneration (waste collection, separation reduction and recycling) represented the 2 domains with more experienced participants, accounting a total of 15 and 13 responses, respectively. Psychology of human isolation and confinement is the most underrepresented domain of expertise, accounting 3 responses. Participants were asked to specify their domains of expertise in the case it was not included in the available answers. The respondents referred to ISRU, submersibles, and the Micro-Ecological Life Support Systems Alternative (MELiSSA) micro-biome.

The participant's profile data provides a validation tool for the surveys' fieldwork. The participants' answers in regard to their profile permits to ensure that the potential entities are selected according to the sampling criteria.

5.2.3 Survey's results: participant's interest in modules and in the opportunities in the modules' technologies.

Participant's responses indicate that water and air (both with 14 answers), waste (13 answers) and greenhouse (12 answers) are the modules with higher research opportunity.

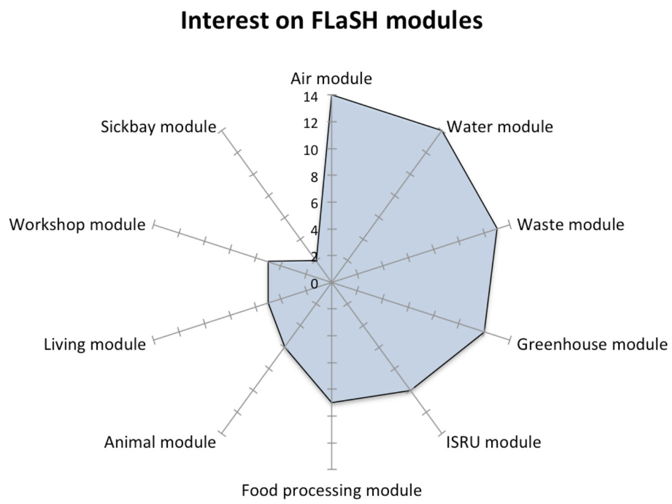

Figure 5-2: Interest of respondents in the different modules. Radial axis represent the number of respondents

The ISRU, Food, Animal, Workshop are the next modules with higher interest. According to the participant's answers, the Sickbay module is the least interesting module, see Figure 5-2. Those results are in line with the results obtained in reference to the areas of expertise. Environment, Biotechnology and Chemistry conform the group of fields with more number of participants. Those fields are the most related to the Air, Water, and Waste modules. Namely, in the Air module 10 out of the 14 answers represent the Environment sector and 5 belong to the Biotechnology and Chemistry. In regard to the Water module, 10 out of the 15 respondents have a background on Environmental sciences as well as in Biotechnology and Chemistry. Data was also analysed in order to study module's preferences variability according to the different types of entities, portrayed in Figure 5-3.

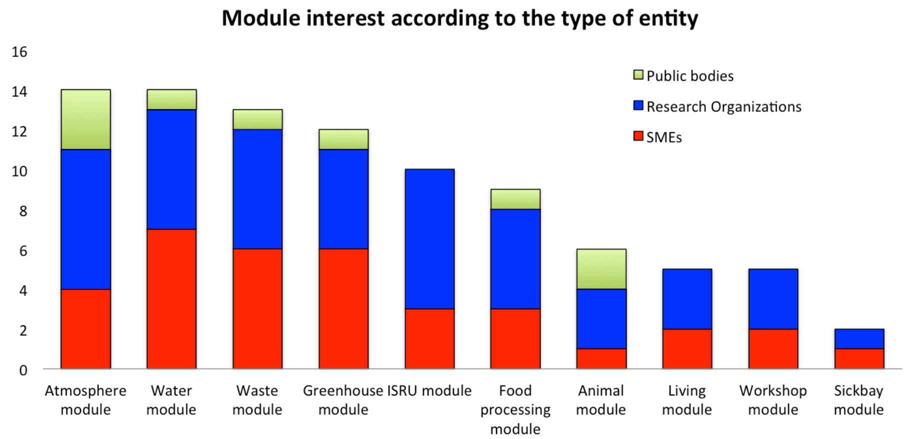

Figure 5-3: Module interest across entity's type.

In Figure 5-3 can be seen that SMEs and research organizations are interested in all modules. However, this not the case for public bodies which did not stated any interest in the ISRU, Living, Workshop and Sickbay modules. Public bodies and agencies are more interested in Air and Animal modules, with 3 and 2 (out of four) interested entities, respectively. The landscape in which different types of organizations share interest in the same modules is considered a positive result, enabling cross-organizational collaboration. Nevertheless, the ideal scenario would be that all type of entities were interested in all modules. Further on, the main results regarding the interest of participants on the modules' technology are presented.

The Air modules' technologies and the number of participants interested in each technology are presented in Figure 5-4. Almost all technologies account for at least one interested participant. Superoxide and reactive plasma beds are the two technologies without any related participant. Superoxide is a non-regenerative technology performing two functions: providing O_2 and trapping CO_2. Potassium superoxide (known as oxygen candle) is the only superoxide manufactured at industrial scales and it is commonly used in mine rescue and fire fighting purposes. Cases of utilization in space are the Vostok space capsule and the Salyut space station. Plasma reaction bed, as seen in chapter 4, is used for trace contaminant control. Those results would not comprise an alleged closed-loop campaign. Superoxide substitutes such as regenerative technologies, for CO_2 trapping and reduction and O_2 generation, account for at least one interested participant. Filters and active charcoals are alternative technologies to plasma reaction bed, performing trace contaminant control functions, and they account for 2 and 4 interested participants.

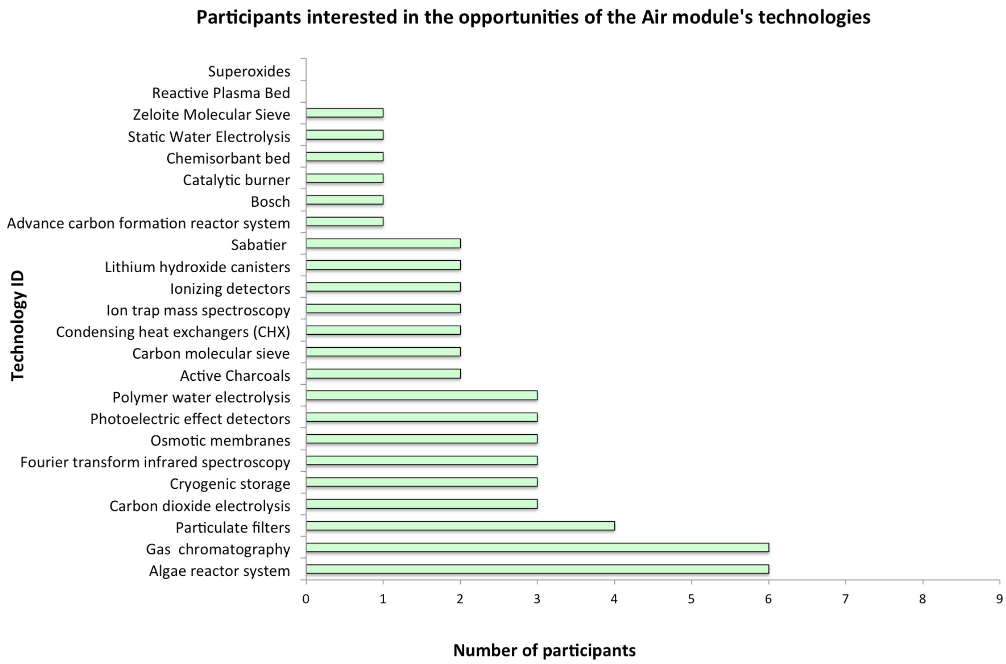

Figure 5-4: number of participants interested in opportunities in Air module's technologies.

The algae reactor and the gas chromatograph are the technologies with higher number of interested participants. Initially, the gas chromatograph high popularity was attributed to its maturity, by the author, since it was invented in 1952 [84]. However, the Ion trap mass spectroscopy, a technology also invented in the 1950s [85], only accounted two interested partcipants. Therefore, more than the maturity of the technology the higher number of interested participants should be due to the sampling bias. It is remarkable that regenerative technologies as zeolite molecular sieves, Bosch reactors, Sabatier reactors and Advance Carbon Reactor (ACR) presented at least one interested participant. This is an important result, in specific for the Sabatier and the Advance Carbon Reactor combo. The Advance Carbon Reactor consists in two elements: a Sabatier reactor, as a gas /liquid separator in order to remove water from methane, and a carbon formation reactor that is in charge for reducing the methane produced (CH_4) into hydrogen and carbon. Carbon will be stored as waste and hydrogen could be reused for the Sabatier reaction itself. Therefore, the Sabatier and Advance Carbon Reactor tandem becomes an important technology when the methane obtained from the Sabatier process is not going to be reused as a propellant.

The number of participants interested in the Water module technologies is presented in Figure 5-5. No respondents had shown any interest in the inductively fluidized bed reactor, plasma reaction chamber, Vapour Compression Distillation (VCD) and the Thermoelectric Integrated Membrane Evaporation System (TIMES). The lack of interested participants in the VCD and the TIMES technologies was an expected result. Considering that VCD and TIMES are NASA development efforts and the applied sampling criteria for selecting survey recipients excluded non-European entities, NASA was not included within the potential entities sample.

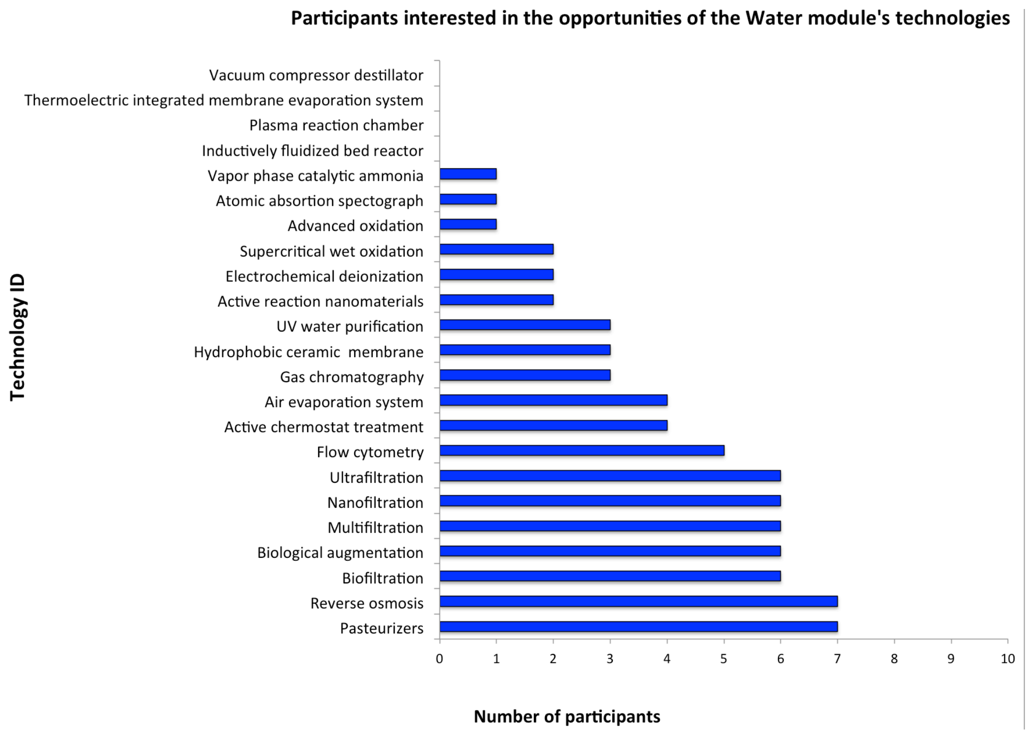

Figure 5-5: number of participants interested in opportunities in Water module's technologies.

However, this is not the case for Vapour Phase Catalytic Ammonia Removal technology (VAPCAR), which surprisingly have a related participant although it is also a NASA's technology. In the worst-case scenario in which none of the NASA technologies have an interested participant, the Combined Regenerator from Organic food Production could perform urine treatment in combination with the Active Chemostat Treatment and the Aquamost technologies.

Promising urine and wastewater technologies were identified, regrettably after launching the questionnaire, thus not being possible to be included within the technological review. This is the case of the Forward Osmosis Bags (FOB). The FOB technology is a very interesting technology since it is an example of a technology conceived and developed for terrestrial purposes (military, refugees, and earth's disaster emergency camps) and afterwards transferred to space. The FOB has been tested satisfactorily at the last Space Shuttle mission and its main objective is to be used as a back-up system [92]. More effort should be directed into finding interested participants in the inductively fluidized bed reactor and the FOB since both of them stand for non-space background technology.

The rest of the technologies within the Water module accounted for at least one interested participant. The highest number of interest answers is found in water treatment microorganisms and reverse osmosis. Reverse osmosis it is a well-established filtration technology and is frequently operated together with other filtration technologies systems as ultrafiltration, multifiltration and nanofiltration. The type of filtration method employed varies according to the size of the particle. Amongst all the filtration systems Reverse Osmosis filters are used to remove the smallest particles (only apt for particles smaller than $1x10^{-7}$ meters). The water fluxes must be pre-treated with other filtration system to remove bigger particles [6], [87]. Therefore, it is a positive result the presence of other entities interested in the rest of filtration techniques. Moreover, the number of participants interested on those other filtration techniques is very similar to the reverse osmosis.

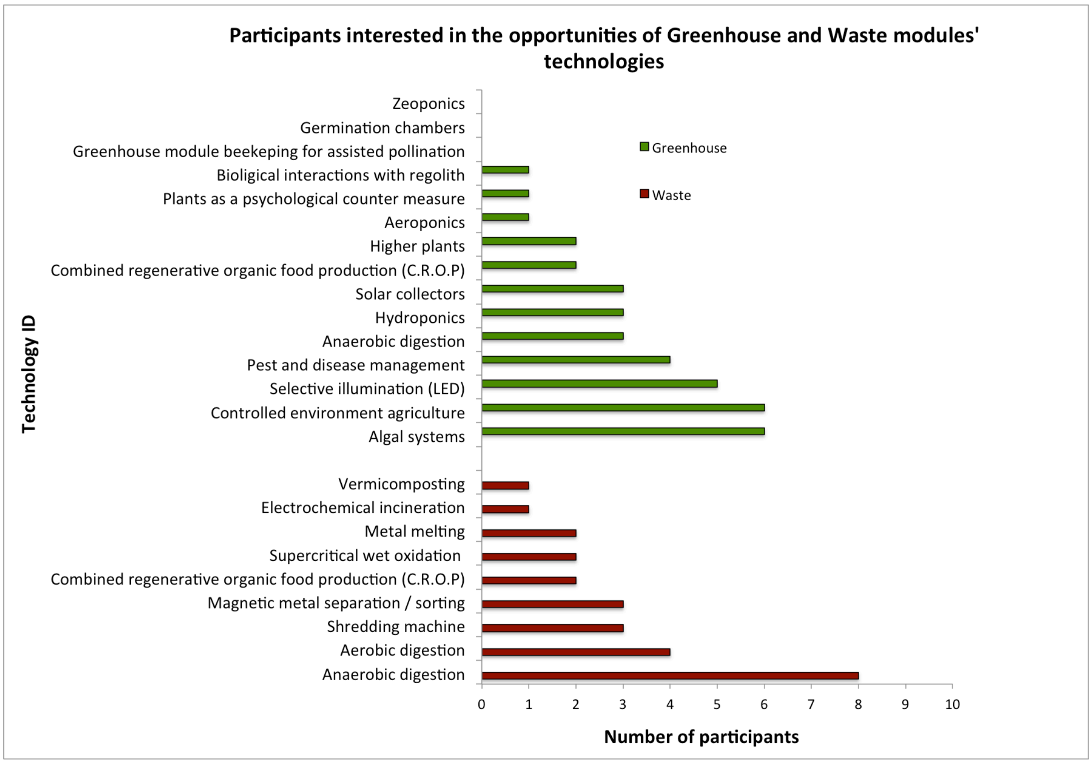

Figure 5-6: number of participants interested in opportunities in Greenhouse and Waste modules' technologies.

Another interesting result regarding participants' interest in the opportunities of the Water module's technologies is found in the Gas Chromatograph technology, which accounts for 3 interested participants for the Water module in contrast to the 6 registered within the Air module. This is a case where participants interested in a technology did not show interest in all the modules where that technology was used. There are two reasons that could explain this pattern:

1. Participants interested in a technology were not aware that the technology could be applied to other modules, thus not stating interest in other modules.

2. Participants were interested into a technology only for the modules they were keen on.

Changing the order in which questions were displayed will help to solve this uncertainty. Recipients were asked to indicate their modules of interest and according to their preferences; the technological options identified for each module were triggered by a sub question. Therefore, future studies must ask before about the interest in technologies and afterwards about the modules of interest. That update will provide participants with awareness about the applications' spectrum of their technologies of interest.

The number of interested participants in the Waste and the Greenhouse modules' technologies are presented in Figure 5-6. The pattern observed for the interested participants in the gas chromatograph is repeated for the Waste and the Greenhouse module with the anaerobic digestion. In the Greenhouse module the participants suggested a research area in addition to the group presented in the survey: biological regolith interactions. Within the Greenhouse module there is no participant related to zeoponics, germination chambers or beekeeping for assisted pollination and honey manufacturing. The germination chambers are considered as relevant equipment since they will assist and ensure the process in which the seed transforms into a plant. However this chambers will vary whether if aeroponics or hydroponics technologies are to be applied. Hence a better strategy will be to implement the germination chamber after growing technologies have been selected or stated. The algal system and controlled environment agriculture turned to be the opportunities within the Greenhouse module's technologies with the highest number of interested participants: 6 participants as in the Air module. Within the waste module all technologies have at least a potential participant, hence being covered all physicochemical and biological relying functions.

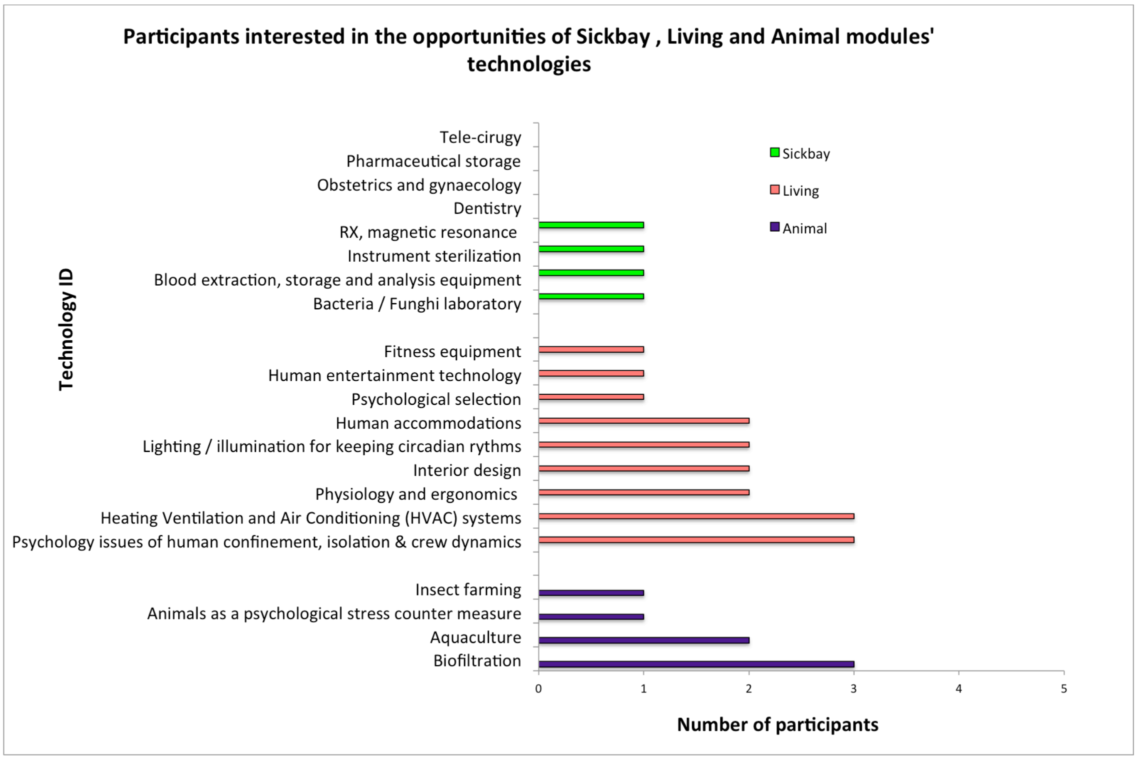

Figure 5-7: number of participants interested in opportunities in Sickbay, Living and Animal modules' technologies.

As for the Living, Sickbay and Animal modules' technologies, only the Sickbay has shown technologies without any related respondent, see Figure 5-7. In regard to the Living module an important psychological aspect not considered during the candidate technologies identification was suggested by a respondent: the psychological selection, i.e. to study crew selection processes to ensure the choice of candidates who will perform and be able to cope with isolation and confinement based on their psychological profile, aptitudes and previous experience. Participants also suggested animals as a psychological counter measure for isolation condition. However, it must be remarked that initially FLaSH only accounted for small animals as fishes and or insects and their effects on human psychology must be studied.

Figure 5-8 presents the number of participants interested in the technologies of the ISRU, Workshop and Food modules. The solid electrolysis technology did not present any related participant. Respondents suggested three research fields: study of microbe rock interaction and conversion of CO_2 into products and salt recovery, water and regolith mineralogy and geochemistry.

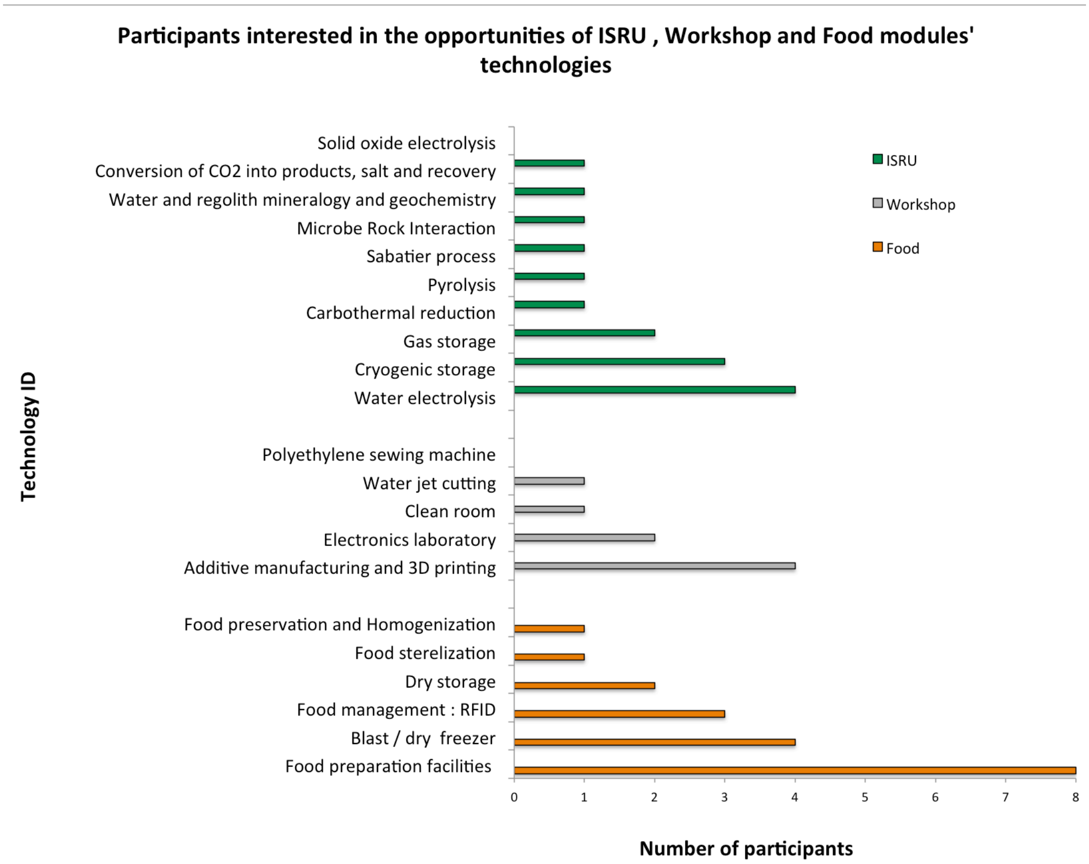

Figure 5-8: number of participants interested in opportunities in ISRU, Food, and Workshop modules' technologies.

The last suggestions are in line with the previously considered purposes of the ISRU module as a provider of LSS consumables and the study geological studies. However, the first suggestion of microbe rock interaction studies brings a new research field to be included in FLaSH: the planetary protection. As defined by ESA planetary protection research aims to prevent microbial life forms travel between moons and planets in our Solar Systems through any device or crew involved in interplanetary missions [88].

In reference to the Workshop module only polyethylene sewing machine lacks from interested participants. This will result into the incapability for repairing crew suits, which were manufactured with polyethylene, according to the FLaSH's preliminary study.

All technologies within the Food module accounted at least one related potential entity, being the dry storage the technology with more related entities. Answers from participants suggested technologies and research domains as food sterilization and homogenization. Those technologies were included within the technology identification as stated in Table 4-4 but only after the survey was launched.

5.2.4 Survey's results: participant's expectations and perceptions

Participants were asked to evaluate their own technological relevance for the operationalization of closed-loop habitats in a scale from 1 (unnecessary) to 10 (crucial), towards the self-reliant habitats. Participants submitted 33 responses instead of the expected 36 (since the question was not mandatory). The most frequent score was 7 (i.e high relevance), with ten participants indicating it and 8 respondents considered low (scoring below 4).

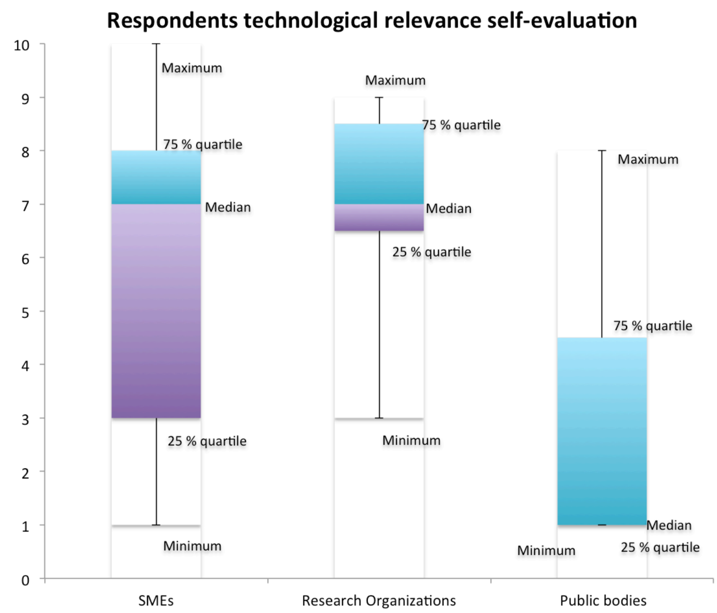

Figure 5-9: Entities self-evaluation of their technological relevance regarding closed-loop habitats.

Strong divergences had been found across type of entities in terms of their technological relevance, Figure 5-9. SMEs responses are more distributed through the whole evaluation scale, whilst in research organization and public bodies responses are more concentrated. In fact, the majority of the research organizations stated high relevance of their technologies, being the 75 % of their answers above 6.5. The highest score within this group is a 9, stated in 4 responses. In public bodies the trend is completely the opposite. Responses are concentrated as well, although on the lower side of the scale. Public bodies scores fall below 4, with an answer stating a score of 8. The highest scores reached the maximum mark of 10, with 3 entities qualifying their technologies as crucial for closed-loop habitats. These entities belong to the group of SMEs.

A total of 27 participants qualify as positive for their entities the outcome / impact of their involvement in FLaSH, i.e. are interested in participation, and 6 participants stated that it was not possible to evaluate the outcome at this early stage of the project. Finally, 3 respondents declared that the participation would not make any difference to their entities. Figure 5-10 presents the geographical distribution of entities declaring positive the involvement in FLaSH. Germany, Belgium and Spain concentrate the highest number of entities expecting a positive outcome from participation in the FLaSH initiative. In Figure 5-11 the expected outcome of participation across the different types of entities is presented.

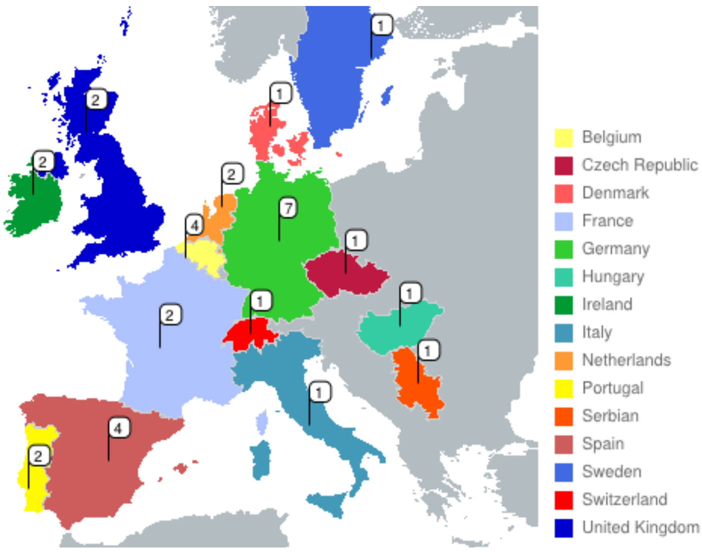

Figure 5-10: Geographical distribution of respondents manifesting interest in participation in FLaSH.

Research organization is the type of entity most convinced that the outcome of participation will be positive. These results are coherent with the research organization's high perspective of their technological relevance in regard to the operationalization of closed-loop habitats as presented in Figure 5-9.

From these responses, it can be inferred that FLaSH will enable geographical and organizational cross boundary collaboration due to the diversity of the type of organizations and the geographical distribution of entities expecting a positive outcome.

A contingency table, see Table 5-1, is presented in order to visualize any trend or relation between the participants perception of their technological relevance towards the facility and the expected outcome. On the top cells the possible expected outcomes are presented. The left column shows the entities' self-evaluation of their technologies for the closed-loop habitats. Cell values indicate the answers' frequency that combines the respective expected outcome with the perception of technological relevance.

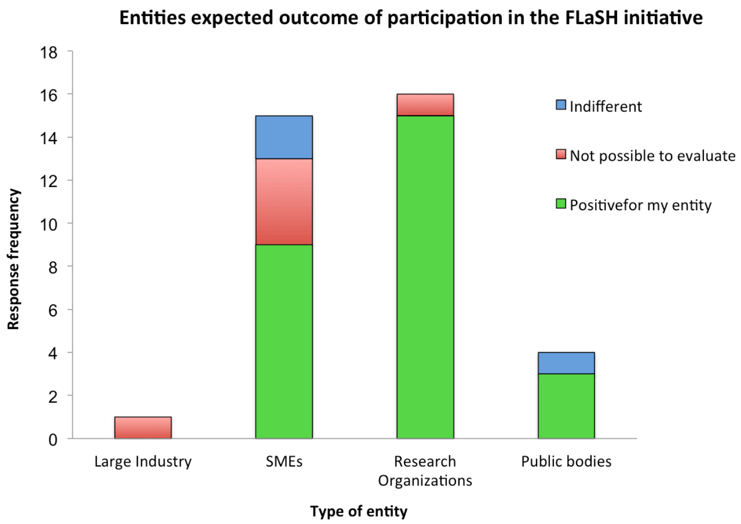

Figure 5-11: Expected outcome from participation in FLaSH according to the type of entity.

Unfortunately, it was not possible to perform any dependency test. Chi-square test requires sample size higher than 50 (in this work only 36 valid responses were obtained) in addition to the fact that several frequency cell values are lower than 5, violating another requirement for performing Chi-squared tests. On the other hand, Fisher's exact test, which is recommended for low size sample and low cell frequency would require the utilization of Montecarlo numerical methods for contingency tables dimensions bigger than 2x2, being that out of the scope of the this work. The author identified that the only remaining action for inverting this scenario was re-launching the questionnaire for obtaining a higher sample size and higher response rates. Nevertheless, those issues do not prevent to obtain valuable insights from the contingency table. With exception of three specific cases, entities with a high perception of their technological relevance tend to state as positive the expected outcome from participation in FLaSH. This is a positive result due to the fact that entities as well as FLaSH will be able to benefit from each other services in a symbiotic relation. Entities will be capable of utilization of FLaSH for performing research on their technological or research domains within self-reliant human habitats as well as FLaSH will benefit from the implementation of entities research / technological domains to provide a self-reliant human habitat. It must be outlined the case in which 3 participants, scoring their technologies within a range between 7 and 9 stated that was not possible to evaluate the outcome of participation.

Table 5-1: Contingency table between entities' technological relevance self-evaluation and expected outcome.

Technology relevance score \ Expected Outcome	Positive for my entity	Not possible to evaluate	Will not make any difference	Row totals
1	1	0	2	3
2	0	2	0	2
3	3	0	0	3
4	0	0	0	0
5	1	0	0	1
6	3	0	0	3
7	8	2	0	10
8	4	0	0	4
9	3	1	0	4
10	3	0	0	3
Column totals	26	5	2	Sum =33

Regarding their relevance, subjected to bias since their technological relevance was self-evaluated, entities in this situation should be involved in next project stages so as to address the reasons for not being confident about the outcome, understand which are they needs and intentions in order to ensure their participation. This must be also applied to the entities with lowest perception of their technologies that expect an irrelevant outcome from participation. Chapter 4 outlined the relevance of technologies that despite not being related to regenerative functions were vital to ensure the operationalization of closed-loop human habitats.

The way participants view their collaboration in FLasH initiative is summarized in Figure 5-12. The majority of the participants preferred to participate through providing advisory services, technology testing and demonstration, and human resources as scientists, engineers and PhD candidates to conduct research in their fields or technologies of interest. In order to not disregard other participation methods that could be of interest for respondents, they were invited to provide other methods. The suggested collaboration methods were:

- Photo bioreactor (PBR) training. Collaboration by providing training for photo bioreactors (PBRs). Training for PBRs can be accounted within advisory services.
- As suppliers and contractors. A respondent suggested collaboration as a material supplier, specifically, LED for the Greenhouse growing chambers. Another respondent proposed collaboration as a contractor providing services or goods.
- Public outreach. Specifically, participation with education, ethics and planetary protection awareness. Those specific actions can be included as Public outreach, which represents the efforts to excite and create awareness about the FLaSH to a wider public.

Other suggestions included scientific collaboration and research and development. The diversity of the term scientific collaboration leads to a wide range of terminologies such as research and development. Scientific collaboration can be understood as the interaction between scientists towards solving complex problems within a variety of social and technical contexts. Scientific collaboration may involve open access to expertise and resources between collaborators cross-disciplinary knowledge exchange and access to funding. Moreover, it will comprehend other methods already presented to the participants as technology testing and human resources. Regarding the wide range of activities covered by scientific collaboration and lacking from a more concise definition it has been considered as another independent method. Therefore, this limitation must be addressed in further studies with specific definition of the activities that will be encompassed under scientific collaboration.

On one hand, technology testing, human resources, scientific collaboration, public outreach are considered as bidirectional loops since all those activities involve the mutual benefit for FLaSH and the entities. On the other hand, methods as advisory, supply and contractors are considered as inputs to the facility, doing “business as usual”.

None of the participants indicated the funding option as a method of contribution. This might be due to the fact that the entities’ contact point was not in the position of stating any budgetary decisions within their respective entities. Despite partnership will concern budgetary aspects, further data collection must be performed in that ambit.

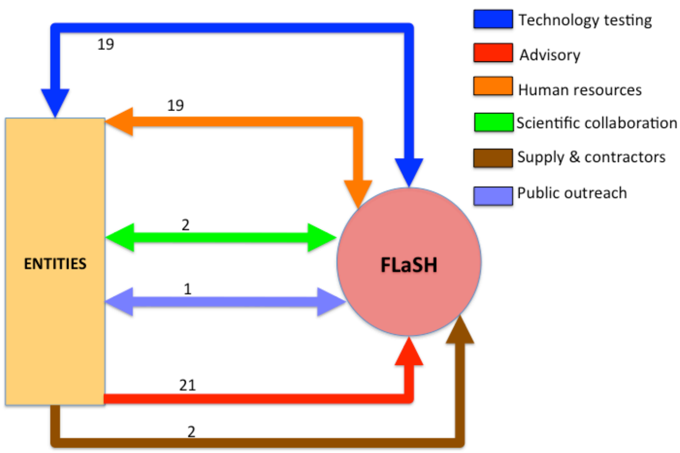

Figure 5-12: Participation methods. Number accounts for the response frequency obtained for each method

In reference to the type of entities, research organizations preferred collaboration method was the provision of human resources for conducting research, followed by technology testing, advisory, scientific collaboration and public outreach. This is an expected result since research organizations collaborate with other entities by mobilization of human resources. SMEs preferred method was technology testing, followed by advisory, human resources provision and supply and contractors. Public bodies’ preferred method was providing advisory services. None of the respondents from the public bodies stated technology testing as a preferred method, an expected result taking into consideration their low self-provided grades in terms of their technological relevance for closed-loop habitats.

Finally, 26 participants consider that closed-loop technologies will achieve a higher development in both environments: Earth and space. This results show that respondents are in tune with the dual approach for technology development for space as well as for terrestrial applications comprehended in FLaSH. Another interesting result is the 6 responses stating a higher development of life support closed-loop technologies for Earth application in front of the 2 stating a higher development of closed-loop technologies for Space applications. These results draw the attention since in the literature research in Chapter 2, closed-loop habitats have had more focus and de development for space applications.

5.3 Results discussion

This section answers to the research opportunity questions proposed in chapter 1. For that purpose the results and information retrieved from the survey will be employed.

5.3.1 Are there entities interested in participation and what is their profile?

Respondents with interest in participation were considered as the participants stating a positive outcome from participation. The survey revealed that a total of 27 entities are interested in participation. In Figure 5-10 and Figure 5-11 were represented the participants stating as positive the outcome of participation in FLaSH according to their geographical distribution and their type of entity, respectively. Within the industry, a total of 9 SMEs are interested. The only big entity participant within industry (entity with more than 250 employees) declared that the outcome was not possible to evaluate at this stage of the project. In research organizations and academia the number of interest entities increases up to 15 interested entities out of the 16 participants. As for the public bodies 3 out of 4 participants are interested.

As mentioned in the survey results discussion, although no dependency test was applicable, from the contingency Table 5-1 was inferred that participants with a higher perception of their technological relevance towards FLaSH are more likeable to state as positive their expected outcome from participation on FLaSH, i.e. to be interested on participation. Recalling Figure 5-9,research organizations and academia responses in regard to the technological relevance were concentrated in the high relevancy values (scoring more than 7) in contrast to the industry responses, which were more spread along the scale. Therefore, it is expected a higher number of research organizations and academia’s respondents interested in participation than within the industry. Draws the attention that for the public bodies and agencies results are the opposite: despite the majority of respondents from this type of entity stated as low their technological relevance, 3 out of the 4 surveyed participants stated interest of participation. For some agencies included in the sample as the European Space Agency (ESA) this result is not surprising. ESA aims at redistributing 85 % of its budget in the form of contracts with the industry, thus relying technology manufacturing and development in other type of entities as the industry [89]. The survey's responses were anonymous, therefore no conclusion could be made regarding the specific role in technology development of the respondent group integrated by public bodies and agencies.

The geographical distribution shows that entities around 15 European countries could benefit from participation in FLaSH. Germany is the country with a higher number of interested participants. Followed by Spain and Belgium with 4 interested participants.

From the 27 potential participants with interest of participation, 21 participants had previous experience in human self-reliant habitats while 6 did not have any experience.

Furthermore, the research opportunity study provided with the profile of most suitable entities for collaborating in FLaSH. The ideal entity can be defined as the entity expecting a positive outcome, i.e. interested in participation, and stating a high perception of their technological relevance within self-reliant human habitats. The survey results have shown that 23 out of 36 participants fall within that definition. They are considered as the most suitable because they provide the most desirable collaboration frame where both parts could benefit from each other; FLaSH will benefit from their technological relevance to operate under closed-loop conditions and the participants will use FLaSH for developing, testing or demonstrating their technologies. On the other side more efforts must directed to involve hesitant participants with high perception of their technological relevance.

5.3.2 According to entities, which are the FLaSH's most interesting modules and technologies?

Air, Water, Waste and Greenhouse modules are the preferred modules in terms of the number of interested participants. This result was in tune with findings obtained in chapter 4, where was concluded that Air, Water, Waste, Greenhouse and Animal modules presented a higher number of opportunities for closed-loop technology testing since they involved all the regenerative functions.

The high interest in the ISRU module with 10 interested participants was not expected. This is a very positive result since FLaSH is intended to work at a 95% of material closure, with the ISRU module in charge for provision the remaining 5 % of the necessary resources to achieve a complete self-reliance state. Furthermore, the ISRU module is expected to place FLaSH as the only LSS infrastructure involving in situ resource reutilization with planetary resources in comparison to the relevant life support systems infrastructures studied in Chapter 2. Additionally, participants interested in the ISRU module suggested a new research field to be included within FLaSH: planetary protection.

The obtained survey's answers regarding the interest of participants in the opportunities of the modules' technologies revealed a total of 16 technologies without any interested participant. In two cases those technologies are utilised for providing basic LSS functions: trace contaminant control and urine treatment. These circumstances do not suppose a threat for the facility operationalization since other technological options to carry those functions, identified in Chapter 4, accounted for at least one related participant. Nevertheless, they represent a loss of research opportunities.

Research organizations, industry and SMEs as well as public bodies share interested in several modules' technologies. This is an encouraging finding considering that FLaSH seeks to promote the scenario in which modules' technologies are related to the three types of entities, creating knowledge transfers across organizational boundaries, hence matching with one of the goals of the Horizon 2020 program. However, there are modules as the Sickbay module where only one type of organization has shown interest. Higher efforts must be directed to seek interested participants belonging to the other organization types. The ISRU, Sickbay and Workshop modules lack of public bodies interested in their technologies. Due to the lower presence of public bodies within the sample was expected that they were not interested in all of the modules.

Results also evidenced a pattern regarding the participants' interest on FLaSH modules' technologies. The number of participants interested in a technology available on multiple modules, varied among modules. Participants indicated the technologies of their interest exclusively within the modules they were keen on. It is not possible to ensure if they did not state interest in other modules because they were not interested or because they were not aware that their technology of interest could be applicable to other modules. A solution for that uncertainty is to change the order in which questions were displayed. Specifically, the new arrangement would display first the technologies included in FLaSH and according to the selected technologies a sub question will be triggered asking the participants to indicate their modules of interest.

Finally the interest in modules' technologies supported the FLaSH idea of providing a closed loop habitat based on the combination of biological and physicochemical technologies, with interest oriented to both types of technology

5.3.3 Which expectations and perceptions do entities have of their role within FLaSH operationalization and utilization?

On the basis of the results yielded in the FLaSH survey can be concluded that participant's perception of their technological relevance is rather high with 78% (25 respondents) of the participants scoring their technological relevance as 5 or higher. Only 8 participants considered their technological relevance as low or very low (less than 4). The results also denoted different perceptions of the technological relevance across the entity types. Research organizations and academia showed a higher perception of their technological relevance with a 75% of participants scoring their relevance as

6 or higher. SMEs presented higher variation in the grades but accounted with 3 participants with the highest perception amongst all the participants, grading as 10 their technological relevance.

The inquired participants were in tune with the FLaSH collaboration methods suggested. Considering that FLaSH aims at providing a technology incubator for closed-loop technologies, it is a positive result that 19 participants are willing to collaborate by using the facility for technology development, test and demonstration. This collaboration method was the preferred within the SMEs while research organizations most preferred method is based in sharing human resources as engineers, scientists, PhDs or students for conducting research.

Although, this work gathered suggestions in regard to collaborations methods, it is recommended to provide a better definition of the collaboration framework. Some respondents suggested scientific collaboration as their preferred way to participate. Scientific collaboration is a very broad term involving already proposed methods within this survey. Consequently, from this work it is encouraged an in deep study of the entities collaboration patterns in order to acknowledge how FLaSH can match their participation preferences.

Finally, according to respondent's expectations, self-reliant human habitats will achieve higher development for both environments: space and terrestrial applications. This is an important result pointing out that the majority of participants share the common vision of FLaSH in regard to the LSS technologies development for terrestrial as well as space applications. However, it must be denoted the higher number of respondents holding the strategic vision that closed-loop technology will achieve a higher development for terrestrial application than for Space. This result supports even more the approach of developing LSS technologies for terrestrial as well as for Space applications.

6 Conclusions

The objective of this work was to study FLaSH's European research opportunity on three levels, represented by the previously suggested questions:(i) Are there entities interested in participation and what is their profile? (ii) According to entities, which are FLaSH's most interesting modules and technologies? (iii) Which expectations and perceptions do entities have of their role within FLaSH operationalization / utilization?

To reach this goal a review of the LSS's literature and the current FLaSH configuration, as a result of a DLR's Concurrent Engineering Facility study in 2012, was conducted together with the identification the FLaSH's candidate technologies.

The literature review revealed that the LSS's main driver is the human system. LSS are in charge to provide the basic human requirements. The 5 main life support areas are: atmosphere, water, food, waste and crew safety management. Long duration missions' LSS will not only address basic human necessities, but will have to provide the conditions to ensure crew wellbeing and a high performance working environment. Long duration missions' LSS will have to adopt resource regeneration, closing air and water loops by means of regenerative technologies. Regeneration can be achieved by technologies based on physicochemical or biological processes. Despite Biological Life Support Systems (BLSS), also known as CELSS, only become advantageous for minimum mission duration of 5 years, they are fundamental for achieving closure of the food loop. On the other hand, non-regenerative technologies are not suitable as primary technologies for long duration missions. However, their high reliability makes them excellent candidates for back-up or emergency systems.

The review of the literature on LSS and FLaSH highlighted that FLaSH's main premise and unique feature in comparison with other LSS facilities resides in its modular design, which enables and facilitates system and subsystem interchange. The study of the similar LSS infrastructures showed that they were preset, from a system and technology configuration standpoint, without any chance of reconfiguration without stopping the ongoing experiments.

Furthermore, the comparison between the LSS infrastructures presented in chapter 2 and FLaSH unveiled that, in terms of closure indexes operation, the CELSS are the most similar infrastructures when considering FLaSH's objective to achieve a 95% of material closure. However, in contrast to the CELSS, FLaSH will involve all three technology types for regenerative functions: bioregenerative and the regenerative / non-regenerative physicochemical technologies. This approach presents an added value to the FLaSH's research on LSS due to the following reasons:

- Will increase the opportunities for research due to the wider spectrum of technologies involved.
- As it has been mentioned, CELSS are only advantageous for mission duration longer than 5 years. For lower mission duration regenerative physicochemical technologies are the most suitable technology option. Moreover, the physicochemical non-regenerative technologies,

although not being suitable for long duration spaceflight, are the best candidates for emergency situations due their high reliability level. Therefore, physicochemical technology solutions hold an important role for the development of LSS, and to support humankind expansion into celestial bodies. For all those reasons, it is very important to understand and be able to predict the interactions between all three types of technologies.

The FLaSH technological review concluded that Air, Water, Waste, Greenhouse, Animal and Food modules are the most interesting regarding the main goal of the facility as an incubator for closed-loop technology. These modules involve the majority of the regenerative functions, which represent the field of application of closed-loop technologies. However, the Living, Sickbay, Workshop and Animal modules are crucial for integrating the human system within the facility and thus could not be disregarded for closed-loop operation.

Another innovative feature in regard to other LSS infrastructures is the integration of an ISRU module for the study of LSS' consumable generation from planetary (e.g. Mars and Moon) in situ resources.

The ISRU module is a critical module to achieve 100% self-reliance since closure rates higher than 95 % will be unattainable due to leakage losses and unrecyclable waste. Indeed, the research opportunity study concluded that the ISRU module was well received by respondents, drawing a higher interest than the Food module (one of the main modules providing LSS' basic functions).

The research opportunity concluded that 27 European entities, from over 15 European countries would benefit from participation in FLaSH. Specifically, 9 SMEs, 15 research organizations and 3 public bodies. Moreover, 23 out of 27 have a high perception of their technological relevance and expect a positive outcome from their participation in FLaSH initiative, meaning that can be considered as ideal potential participants.

The distribution of participants evidenced that FLaSH will provide a proper scenario for cultivation and enable collaboration across geographical boundaries as well as organizational boundaries between research organizations, industry and public bodies / agencies.

Entities preferences concerning the participation methods supported the FLaSH's intention of providing an arena for technology development, testing and demonstration, although participants preferred collaboration method was as advisory services providers.

Finally, 26 participants reinforced the dual approach of FLaSH in order to develop closed-loop technologies for terrestrial as well as for space applications.

7 Future work

Two approaches have been identified as relevant for future work within this area: technical and organizational.

From the technical perspective, next steps should evaluate the proposed technologies with the Equivalent System Mass method (ESM). This approach will provide a better understanding of the technologies advantages and disadvantages in terms of maintenance time, power requirements, mass, reliability and suitability for Space or terrestrial missions.

Furthermore, the definition of functionalities and technologies involved within the energy/power module must be addressed. Higher material closure degrees come along with higher power requirements; therefore, finding sustainable manners to produce and recycle energy will be critical for the facility operation. Additionally, the energy/power module study will also increase the research opportunities for the facility. Besides, additional work must directed into including a higher number of non-space driven technologies. As it has been suggested in chapter 4, patent databases represent interesting sources for new technology identification, since these will stand for technologies in very early stages.

On the organizational side, the diversity of the interested entities and the limitations observed regarding the definition of the collaboration methods have evidenced the necessity for a better identification of the needs and expectations of participant entities according to their organization type. In order to overcome this limitation an in-depth stakeholder analysis is recommended. As a result a stakeholder network can be created, followed by the identification of their expectations, needs and delivery flows. Additionally, the stakeholder analysis can be used for architecting the FLaSH system in order to ensure that the FLaSH capabilities match the stakeholders' demands.

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Appendix A. Human requirements

Atmosphere

As mentioned the human body can stand periods up to 4 minutes without oxygen, the metabolic rate of oxygen consumption per day per man is Table 2-2. Nevertheless, the provision of oxygen is not the only need of the human body. For a breathable and comfortable atmosphere other gases are needed, known as make up gasses The total atmosphere pressure will be equal to the sum of all partial pressure of all gasses involved [96]:

$$PB = pO_2 + pN_2 + pO_2 + pCO_2 + pH_2O + \cdots + pX_n \quad \textbf{(8-1)}$$

Where the PB is the total barometric pressure, the prefix *p* denotes the partial pressure and O_2, N_2, CO_2 and H_2O represent the components in the atmosphere. Often, in first order approximations other gases than the O_2 and the inert gas, in this case N_2, are not considered. Therefore; reducing expression to:

$$PB = pO_2 + pN_2 \quad \textbf{(8-2)}$$

Considering sea level conditions and the standards given by:

Reference	P [kPa]	pO_2 [kPa]	pCO_2 [kPa]
Sea level	101.3	21.3	0.04
NASA standards (max. & min.)	99.9-102.7	19.5-23.1	<0.04

Temperature and Humidity

Temperature and humidity covers the aspect of habitability regarding the climate presented in Figure 2-6. It is recommended to maintain the habitat humidity and temperature control within a comfort box with the specific values of 25-70 % of relative humidity and temperature of 18.3-26.7 °C for the total duration of the mission and excluding specific operations of duration of less than 4 hours and hatch open after landing [96] and

Trace contaminant control

Missions of more than 30 days in closed –loop must keep track of volatile contaminants; e.g. alcohols, aldehydes, aromatic carbohydrates. For a complete list of the maximum allowance Trace Gas Contamination refer to [16].

Hygiene

The Hygiene aspect is very important not only from the physiological perspective but also from a psychological one. Personal hygiene eliminates microorganisms and avoids the spread of disease as well as increasing the comfort of the crew. From the psychological perspective grooming can enhance self-esteem, improving the morale, fact that it can lead into an increase in productivity.

Sleep

Sleep is a physiological need of the human body with impact in the overall crew comfort and performance. Studies determined that with sleeping periods below 8 hours results in a decrease of the cognitive performance of the crew. Furthermore, subjects restricted to 4 hours of sleep per day for a 14 day period show the same decrease in peak performance than a subject with continuous sleep deprivation for two days. Sleeping periods of less than 8 hours may be allowed for short lapse time.

Noise

The sound is a physical disturbance in the air. That sound regarding the human body can be whether enjoyable or undesired and annoying [18]. The latter is the disturbance defined as noise and it is known for being the source of:

- Stress problems and sleep depravation
- Lowering cognitive performances.
- Cause physical illness and permanent loss of hearing due to long period expositions.

Noise requirements will vary depending on the country and region [97]. Considering that different nations have different legislations and considering that the audition performance it is not affected by environments of reduced gravity the NASA STD-3001 appeals to apply the regular standards on Earth.

The equivalent noise pressure level is an approach for averaging all the noise sources and their frequencies. International standards set a sound pressure level for occupational purposes of 85 dB (A) (8 hours working averaged per week) by the ISO 1999:1990. However those values do not warranty the safety of the auditory system, thus EC directives set the maximum level on 80 dB (A). The unit A stands for "weighting filter A" which is developed in order to account the effect of the variation of the human sensitiveness for the range of audible frequencies. The frequency weight filters permits to weight the contribution of a specific filter to the overall pressure level [98].

The equivalent noise pressure levels may never overcome the 110 dB, value at which hearing loss and damage is induced. Noise can also act as a stressor by reducing memory capabilities

Vibrations

Human sensitivity limits for vibrations are given in the ISO 2631, since the human body can be exposing to vibration for the whole body or isolated parts. The NASA STD-3000 refers different levels of vibration for non-sleep phases, sleep times, vibrations limits for performance and hand vibrations. In Figure A 1, the different vibration limits applied to the different body parts are presented:

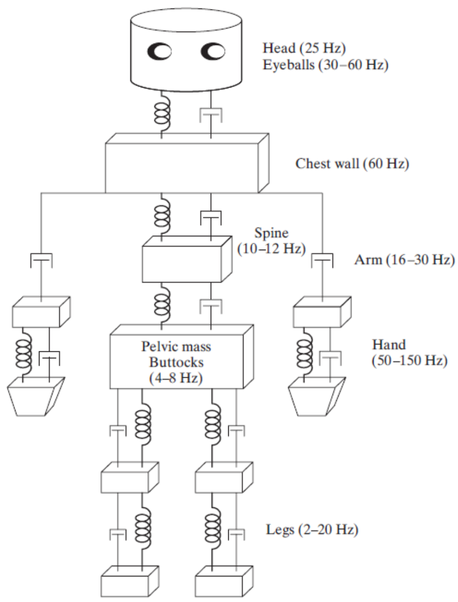


Figure A 1: Sensitivity of vibration for the different parts of the body [99]

Lighting

Lighting needs must take into consideration tasks demands (not only intensity but also color), architectural features (prevision of shadow regions and glare) and luminance adaptation. Furthermore, lighting conditions must ensure synchronization with the wake – sleep cycles and entrainment of circadian cycle.

Circadian cycle entrainment is influenced by diverse environmental stimuli, being the exposition to bright light the most relevant [100].

Radiation

Radiation protection is another aspect to consider for the human health. There are different types of radiation (ionizing and non-ionizing) and regarding space flight above Earth´s radiation belts is the. Radiation limits depend on age, gender and size as well as the type of organs or tissues that are receiving the radiation: NASA requirements set radiation limits between 1 to 3 Sieverts [Sv] for a year and a maximum to 6 Sv in skin for a career time [96].

Acceleration

The excess as well as the lack of acceleration may have impacts on the human body. Regarding the excess of acceleration the system must limit the duration depending the magnitude and direction, see Figure A 2.

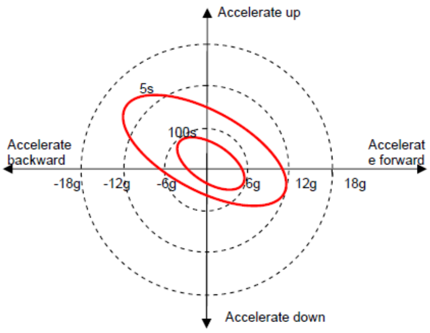


Figure A 2: Acceleration magnitude, direction and time limits. [101]

Regarding the lack of acceleration, microgravity environments induce several physiological changes as: space motion sickness, fluid shifts, and bone demineralization, muscle atrophy, hematological and hormonal changes [5].

Food

The food has been previously defined as one of the critical consumables for ensuring human survivability. Nevertheless, the type of nutrients required, menu planning, and quality have a direct impact not only in the wellbeing of the crew but also in their morale. The top ten ranking of preferred food by the astronauts is provided at [68].

Space and interior layout

Interior space and layout main goal is to ensure the wellbeing of the human crew by providing the best space and distribution for the maximum working efficiency and comfort during the duty and off duty times. The main drivers for the interior size and layout are: mission time, number of crewmembers, gravity environment, mission objectives, stowage and mass and power mission requirements. Three terms are in use to describe the spacecraft / habitat size [96]:

- The total pressurized volume
- The habitable volume also known as the “sand volume”. Corresponds to the resulting volume from the subtraction of the volume occupied by the lab-racks or hardware to the total pressurized volume.
- Net Habitable Volume (NHV) refers to the functional volume remaining for the crew after deployment of all equipment, stowage and all possible architectural deficiencies.

Since minimum NHV drives the design of the overall spacecraft size minimum NHV estimation is recommended during the design phase. There are two processes for calculating the NHV: the task evaluation method and the experience-based method. The task evaluation method consists in the study of the required space for all the duties and activities the crew will perform inside the habitat considering if they are suited or unsuited. The experience-based method relies on data from previous missions. The NHV presents different figures of merit depending on the gravity environment:

- Microgravity: figure of a merit in m^3. For microgravity environments the NHV is computed as a volume.
- Gravity: figure of merit in m^2. In the case of environments with gravity the NHV is computed in terms of square meters despite the name includes the term of Volume. The reason to keep the term volume is due to a minimum of 2,5 m^2 standard, depending on the gravity environment where the habitat is placed. For this particular case, the experience-based value relies on previous subaquatic habitat missions.

Living space on spacecraft's or space habitats can be also determined with a parametric relation, known as the Celentano curves [102].

$$\frac{V}{CM} = A(1 - e^{-\frac{duration}{B}}) \qquad \textbf{(8-3)}$$

Where A can attain three accommodation levels: "tolerable" (A=5), "performance" (A= 10), "optimal" (A=20). The *B* is a scale factor in day units, defined as 20 days.

Finally, for long-term habitation, the habitat pressurized volume per crewmember (i.e. living volume and working volume) should not be lower 120 m^3 [24]. The manner, in which the available space could be distributed according to the activities to be carried, is known as "zooning", addresses zooning regarding the privacy of the activities and if they are carried out collectively or individually, see Figure A 3:

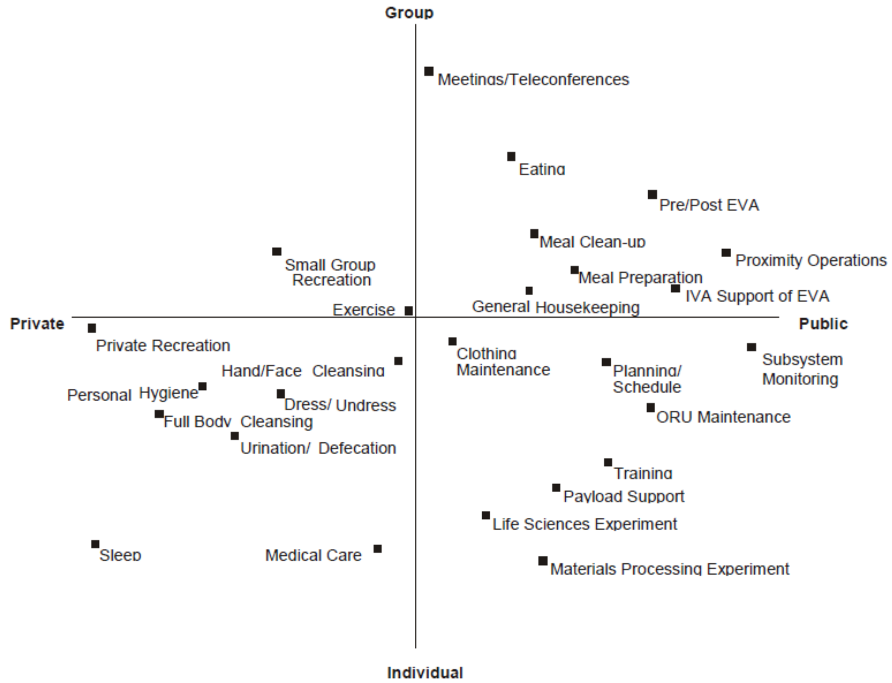


Figure A 3: Activities distribution regarding privacy and team- working requirements [26].

Psychological aspects

An increase of the mission durations for space exploration leads to a higher impact of psychological and interpersonal factors in human crew behaviour and performance [103]. Being those factors hard to quantify, they will be addressed in a broader manner that the rest of the human aspects. As presented in Figure **2**-**6**, those factors involve long duration mission aspects as: like crew schedule, crew composition, interpersonal dynamics, and communication are factors to be considered.

- **Psychiatric aspects:** Some mental health problems are more frequent during space missions and most of the reported are just adjustments reactions to external stressors: e.g. depression due to isolation in orbit. Psychosomatic problems and, to a lesser extend, psychiatric disorders, have been noticed in space analogues and submarines scenarios. That is not the case of spaceflight since potential astronauts undergo an intensive psychological screening [104].
- **Communications:** in a mission involving long distances no real time communication will be possible increasing the isolation factor.
- **Crew composition and interpersonal dynamics:** productivity and performance are related to the form of crew interactions and it is important to consider psychosocial issues and the crew selection. Main issues to regard are: alienation, the host-guest problem, minority status and organizational culture, psychological closing, autonomous level, and displacement and crew autonomy.

- **Schedules:** It is important to implement schedules with duty and duty-off times balance, meal periods and housekeeping activities. An unbalanced schedule can lead to irritability, stress increase and decrease in crew performance.

In order to reduce the effects of those factors different counter-measures may be applied [14] [5].

Appendix B. Graphic support for survey respondents' profile

This appendix provides with the graphical references to the demographic profile of survey recipients and respondents.

Survey Demographic profile of respondents

Geographical respondent distribution in Figure A 4:

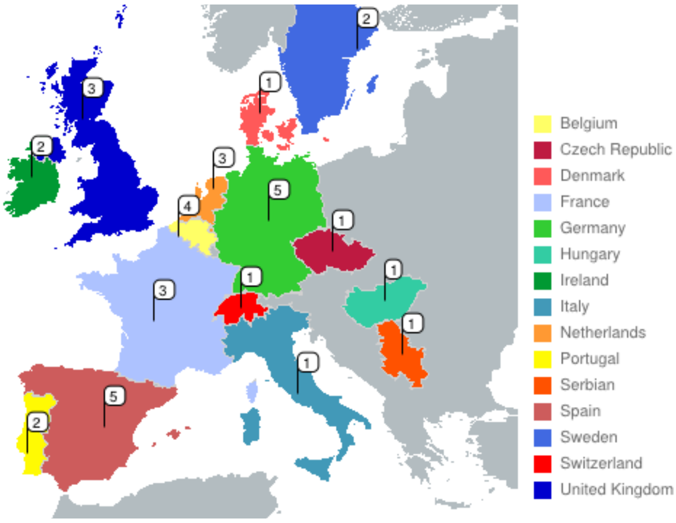


Figure A 4: Geographical distribution of respondents

Responses across entities' activity sector in, Figure A 5:

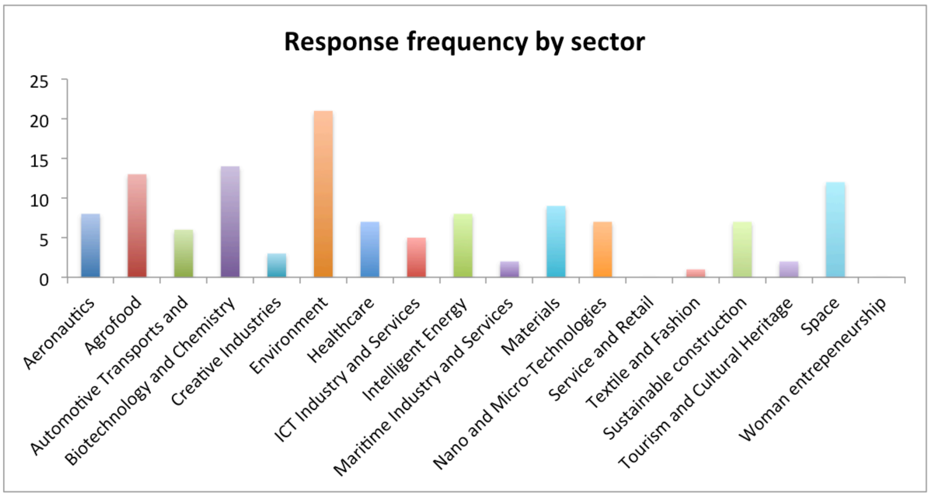


Figure A 5: Respondents distribution by activity sector

Appendix C. Questionnaire

Screenshots from the FLaSH questionnaire:

FLaSH for Thesis reference

Welcome to the Facility of Laboratories for Sustainable Habitation survey! The aim of this brief questionnaire is to support a research potential study of a materially closed-loop infrastructure within Europe.

Facilitiy of Laboratories for Sustainable Habitation (FLaSH)

0%

PARTICIPANT PROFILE

Question group dedicated to gather demographic data related to the participants

A1 * Which type of entity are you working for?
Choose one of the following answers

- ○ Public bodies (e.g. agencies).
- ○ Industry and Small & Medium Enterprises (SMEs).
- ○ Research organization and academia (e.g. universities).
- ○ Other:

A1C * How many employees are currently working in your entity?
Choose one of the following answers

- ○ Less than 50.
- ○ Between 50 and 249.
- ○ 250 or more.

A2 * In which area(s) would you place the activities / services of your entity?
Check any that apply

- ☐ Aeronautics.
- ☐ Agrofood.
- ☐ Automotive, Transports and Logistics.
- ☐ Biotechnology and Chemistry.
- ☐ Creative Industries.
- ☐ Environment.
- ☐ Healthcare.
- ☐ ICT Industry and Services.
- ☐ Intelligent Energy.
- ☐ Maritime Industry and Services.
- ☐ Materials.
- ☐ Nano and Micro-Technologies.
- ☐ Service and Retail.
- ☐ Textile and Fashion.
- ☐ Sustainable construction.
- ☐ Tourism and Cultural Heritage.
- ☐ Space.
- ☐ Woman entrepeneurship.
- ☐ Other.

? *Please, check more than one box in case your activities reach multiple fields.*

A3 * Which is the nationality of your entity?
Check any that apply

- ☐ Austria.
- ☐ Belgium.
- ☐ Bulgaria.
- ☐ Croatia.
- ☐ Cyprus.
- ☐ Czech Republic.
- ☐ Denmark.
- ☐ Estonia.
- ☐ Finland.
- ☐ France.
- ☐ Germany.
- ☐ Greece.
- ☐ Hungary.
- ☐ Ireland.
- ☐ Italy.
- ☐ Latvia.
- ☐ Lithuania.
- ☐ Luxemburg.
- ☐ Malta.
- ☐ Netherlands.
- ☐ Poland.
- ☐ Portugal.
- ☐ Romania.
- ☐ Slovakia.
- ☐ Slovenia.
- ☐ Spain.
- ☐ Sweden.
- ☐ United Kingdom.
- ☐ Other: ____

? *Feel free to check more than one box in case of multipe- nationalities*

Resume later | ◂ Previous | Next ▸ | Exit and clear survey

B1 * Which field(s) are you more familiar with?

- ☐ Closed-loop technologies.
- ☐ Efficient resource utilization.
- ☐ Self-reliant human habitats.
- ☐ Resource reclamation.
- ☐ None of them.

B2 * Have any of your activites or services ever been involved with: self-reliant human habitats, closed-loop technologies, efficient resource utilization and / or resource reclamation?

○ No. ○ Yes.

B2A * In which of the following domains?
Check any that apply

- ☐ Atmosphere regeneration and control.
- ☐ Aquaculture and insect farming.
- ☐ Controlled environment agriculture.
- ☐ Food processing, preparation, storage and management.
- ☐ Habitation.
- ☐ Manufacturing techniques and processes.
- ☐ Medical equipment.
- ☐ Psychological / physiological issues of long-term confinement and isolation conditions.
- ☐ Waste collection, reduction, separation and recycling.
- ☐ Water collection, treatment and reclamation.
- ☐ Other: ____

? *Check more than one option for multiple domains.*

Resume later | ◂ Previous | Next ▸ | Exit and clear survey

C1 * Which module domain would be of interest for your entity?
Check any that apply

- ☐ Atmosphere module.
- ☐ Water module.
- ☐ Waste module.
- ☐ Food processing module.
- ☐ Animal module.
- ☐ Greenhouse module.
- ☐ Sickbay module.
- ☐ Living module.
- ☐ Workshop module.
- ☐ In-situ resource utilization.
- ☐ None of them.

C1A * Considering your interest for the Atmosphere Module, could you indicate if your entity is related to any of the following technologies / services? (If none of them are applicable, please specify which technology /service your company is related with).
Check any that apply

- ☐ Active charcoals.
- ☐ Advance carbon formation reactor system.
- ☐ Algae reactor / systems.
- ☐ Bosch process.
- ☐ Carbon dioxide electrolysis.
- ☐ Carbon molecular sieve.
- ☐ Catalytic burner.
- ☐ Chemisorbant beds.
- ☐ Condensing heat exchangers.
- ☐ Cryogenic storage.
- ☐ Fourier transform infrared spectroscopy.
- ☐ Gas chromatography.
- ☐ Ionizing detectors.
- ☐ Ion trap mass spectroscopy.
- ☐ Lithium hydroxide canisters.
- ☐ Osmotic membranes.
- ☐ Particulate filters.
- ☐ Photoelectric effect detectors.
- ☐ Polymer water electrolysis.
- ☐ Reactive bed plasma.
- ☐ Sabatier process.
- ☐ Static feed water electrolysis.
- ☐ Superoxides.
- ☐ Zeolite molecular sieve.
- ☐ Other: ____________

C1B * Considering your interest for the Water Module, could you indicate if your entity is related to any of the following technologies / services? (If none of them are applicable, please specify which technology /service your entity is related to).
Check any that apply

- ☐ Active chermostat treatment.
- ☐ Active reaction nanomaterials.
- ☐ Advanced oxidation.
- ☐ Air evaporation system .
- ☐ Atomic absorption spectograph.
- ☐ Biological augmentation.
- ☐ Biofiltration.
- ☐ Electrochemical deionization.
- ☐ Flow cytometry.
- ☐ Gas chromatography.
- ☐ Hydrophobic ceramic membrane.
- ☐ Inductively fluidized bed reactor.
- ☐ Microbiological water treatment (pasteurizers).
- ☐ Multifiltration.
- ☐ Nanofiltration.
- ☐ Plasma reaction chamber.
- ☐ Reverse osmosis.
- ☐ Supercritical wet oxidation.
- ☐ Thermoelectric integrated membrane evaporation system.
- ☐ Ultrafiltration.
- ☐ UV water purification.
- ☐ Vacuum compressor destilator.
- ☐ Vapor phase catalytic ammonia.

C1C * Considering your interest for the Waste Module, could you indicate if your entity is related to any of the following technologies / services? (If none of them are applicable, please specify which technology /service your entity is related to).
Check any that apply

- ☐ Aerobic digestion.
- ☐ Anaerobic digestion.
- ☐ Combined Regenerative Organic Food Production (C.R.O.P).
- ☐ Electrochemical incineration.
- ☐ Supercritical water oxidation.
- ☐ Shredding machine.
- ☐ Magnetic metal separation / sorting.
- ☐ Metal melting.
- ☐ Vermicomposting.
- ☐ Other: ____

C1D * Considering your interest for the Greenhouse Module, could you indicate if your entity is related to any of the following technologies / services? (If none of them are applicable, please specify which technology /service your entity is related to).
Check any that apply

- ☐ Aeroponics.
- ☐ Anaerobic digestion.
- ☐ Algal systems.
- ☐ Beekeping for assisted pollination.
- ☐ Controlled environment agriculture.
- ☐ Combined Regenerative Organic-Food Production (C.R.O.P.).
- ☐ Germination chambers.
- ☐ Higher plants.
- ☐ Hydroponics.
- ☐ Pest and disease management.
- ☐ Selective illumination (LED).
- ☐ Solar collectors.
- ☐ Zeoponics.
- ☐ Other: ____

C1E * Considering your interest for the Animal Module, could you indicate if your entity is related to any of the following technologies / services specified below? (If none of them are applicable, please specify which technology /service your entity is related to).
Check any that apply

- ☐ Aquaculture.
- ☐ Biofiltration.
- ☐ Insect farming.
- ☐ Other: ____

C1F * Considering your interest for the Living Module, could you indicate if your entity is related to any of the following technologies / services? (If none of them are applicable, please specify which technology /service your entity is related to).
Check any that apply

- ☐ Fitness equipment.
- ☐ Heating Ventilation and Air Conditioning (HVAC) systems.
- ☐ Human accommodations.
- ☐ Human entertainment technology.
- ☐ Lighting / illumination for keeping circadian rythms.
- ☐ Interior design.
- ☐ Psychology issues of human confinement, isolation & crew dynamics.
- ☐ Physiology and ergonomics.
- ☐ Other: ____

C1G * Considering your interest for the Sickbay Module, could you indicate if your entity is related to any of the following technologies / services? (If none of them are applicable, please specify which technology /service your entity is related to).
Check any that apply

- ☐ Bacteria / Funghi laboratory.
- ☐ Blood extraction, storage and analysis equipment.
- ☐ Dentistry.
- ☐ Isntrument sterilization.
- ☐ Obstetrics and gynaecology.
- ☐ Pharmaceutical storage.
- ☐ RX, magnetic resonance or ohter medical diagnostic equipment.
- ☐ Tele-cirugy.
- ☐ Other: ____

C1H * Considering your interest for the Food Processing Module, could you indicate if your entity is related to any of the following technologies / services? (If none of them are applicable, please specify which technology /service your entity is related to).
Check any that apply

- ☐ Blast / dry freezer.
- ☐ Dry storage.
- ☐ Food management : RFID.
- ☐ Food preparation facilities (stove, oven, microwave, coffee machine, dishwasher,etc...).
- ☐ Other: ______

C1I * Considering your interest for the Workshop Module, could you indicate if your entity is related to any of the following technologies / services? (If none of them are applicable, please specify which technology /service your entity is related to).
Check any that apply

- ☐ Additive manufacturing and 3D printing.
- ☐ Clean room.
- ☐ Electronics laboratory.
- ☐ Polyethylene sewing machine.
- ☐ Water jet clutting.
- ☐ Other: ______

C1J * Considering your interest for the ISRU Module, could you indicate if your entity is related to any of the following technologies / services? (If none of them are applicable, please specify which technology /service your entity is related to).
Check any that apply

- ☐ Carbothermal reduction.
- ☐ Gas storage.
- ☐ Cryogenic storage.
- ☐ Pyrolysis.
- ☐ Sabatier process.
- ☐ Solid oxide electrolysis.
- ☐ Water electrolysis.
- ☐ Water reverse gas.
- ☐ Other: ______

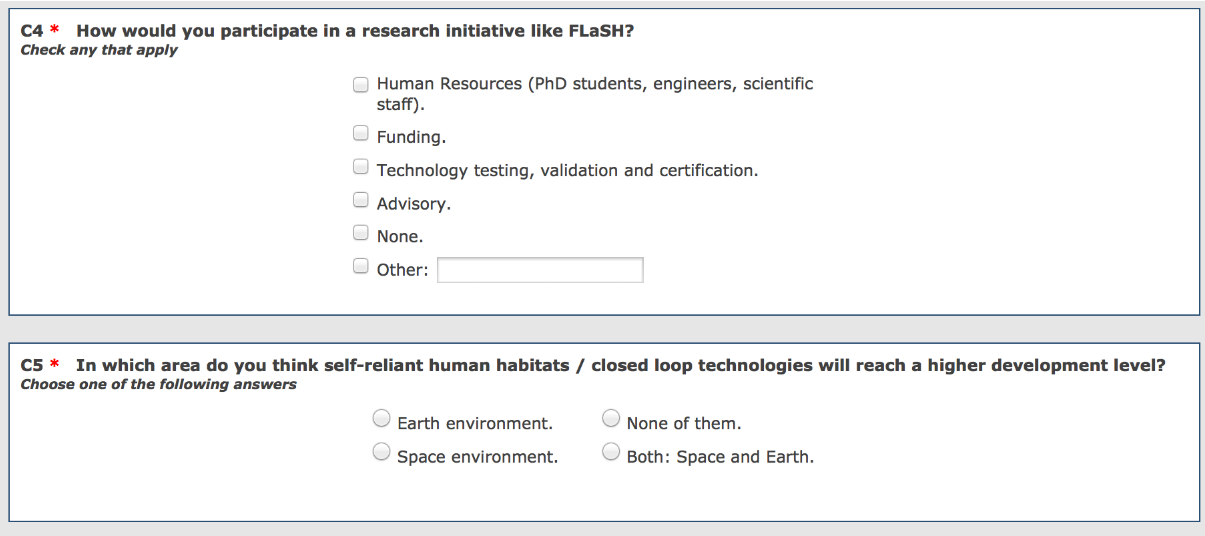
C2
How would you classify the relevance of your technologies / services regarding self-reliant human habitats?

	1	2	3	4	5	6	7	8	9	10	No answer
Relevance.	○	○	○	○	○	○	○	○	○	○	◉

Please regard that prescindible=0 and essential=10

C3 * In your opinion, the participation of your entity in the FLaSH research initiative will be:
Choose one of the following answers

- ○ Positive for my entity.
- ○ Negative for my entity.
- ○ Will not make any difference for my entity.
- ○ Not possible to evaluate.



C4 * How would you participate in a research initiative like FLaSH?
Check any that apply

- ☐ Human Resources (PhD students, engineers, scientific staff).
- ☐ Funding.
- ☐ Technology testing, validation and certification.
- ☐ Advisory.
- ☐ None.
- ☐ Other:

C5 * In which area do you think self-reliant human habitats / closed loop technologies will reach a higher development level?
Choose one of the following answers

- ○ Earth environment.
- ○ None of them.
- ○ Space environment.
- ○ Both: Space and Earth.

Participants profile

This set of questions aims to draw information in regard to respondent participants, the type, their size/volume, their geographical distribution, their activities and if they have previous experience in any of the FLaSH previous modules.

Question A1

The first question gathers information regarding the type and nature of the entity. Three different pre-defined responses were available: public entities (i.e. agencies), Industry companies and SMEs, and Research Organizations and academia These three categorizations concerns to all the entities capable of applying to Horizon 2020 projects according to the program's online manual [105]. The option of "other" was provided in case the respondents were willing to provide with more information or do not fit into the choices available.

Question A1B

The second question determines the size of the entity. The scale employed follows the patterns defined by the European Commission [106] for enterprises. Due to lack of other scales for measuring the size of agencies or research organizations and academia, the same reference scale was applied to them.

Question A2

The third question collects information regarding the different fields of expertise and backgrounds of the entities. The list of fields presented as potential answers, embraces the areas discretized by the European Commission [107]. The question is defined as a multiple-choice question since a single entity can develop its activities in different areas simultaneously.

Question A3

The last question of first section of the questionnaires collects the geographical information of the company.

Participants awareness and previous experience

The questions within this section aim to determine weather if the Participants are aware of self-reliant human habitats and if they have any previous experience with the main research domains of FLaSH.

Question B1

The first question is dedicated participant awareness intends to determine whether the participant is familiar with any of the aspects related with self-reliant habitats: closed-loop technologies, efficient resource utilization, self-reliant human habitats, and resource reclamation.

Question B2 and B2A

Question B2 it is a binary-answer question to identify if the participant had any previous experience in self-reliant habitats, efficient resource utilization, and reclamation or closed-loop technologies. In the affirmative case it leads to a sub question where the respondent is asked to identify in which of the FLaSH areas the previous work was related with.

Participants preferred modules and linkage to modules' technologies, their perceptions and expectations in regard to participation in FLaSH and its development.

This group of questions is dedicated to draw the most relevant information in order to answer the questions of the research opportunity proposed in chapter 1. Questionnaire recipients are asked to indicate which modules are of their interest, to which modules' technologies are they related, how they perceive their role in regard to the operationalization of the facility and their expectations

Question C1

In order to assess which specific module / research domain presents a higher number of interested Participants, recipients were asked to designate which FLaSH module presents a higher appeal for their entities, if any. This is a multiple-choice question since the participant could be interested in several modules

Question C1A-C1B-C1C-C1D-C1E-C1F-C1G-C1H-C1I-C1J-

This group of sub question, triggered by question C1, it is intended to provide more insightful information in reference to the modules research opportunity. Specifically, participants were asked to indicate which technologies are related to their activities. Moreover, considering the limitations encountered in the potential technology identification in chapter 4, and in order to mitigate them, participants were also encouraged to suggest any other technology or research field to which they were related to or interested whilst was not included. For that purpose an open-end answer text box was available within the question.

Question C2

This question intends to determine how participants evaluate the role of their technologies towards self-reliant human habitats. This is defined as ratio question since the participant include their relevance in a scale from 1 (unnecessary) to 10 (very important or crucial). Since this query involves an internal judgment of the respondents of their own technologies, the question was defined as not mandatory allowing respondents to skip the question (preventing them from quitting before filling the following questions).

Question C3

In this question participants are asked to provide their opinion on which outcomes their participation or use of the FLaSH infrastructure can deliver to their respective entities. For this question 4 possible answer were available for respondents: positive for my entity, not possible to evaluate or will not make any difference for my entity. The first option allows considering the entity willing participating, while the second does not allow retrieving any conclusion regarding their interest. When entities stated "will not make any different for their entity" they could considered as an entity, at this stage, not interested to take part in the initiative (this fact does not mean that in further phases of the project they could become interested and would engage in the project).

Question C4

This question gathers information regarding the way the participants suggest being involved and engaged with the initiative. Four options were available:

- Technology testing and demonstrator. Participation is based on using the infrastructure for LSS technology testing and demonstration purposes.
- Human resources (PhD students, engineers, scientific staff). Although not using the facility as a technology test bed or demonstrator, prospective participants might also be interested in collaboration through the allocation of human resources for conducting research in any of the possible research domains, as crew members for test runs in closed loop operations or management positions.
- Funding. Potential participants will establish collaboration through funding of research programs or any other activity or aspect involved in the facility.
- Advisory services. Entities will participate by providing advisory and consulting services in any aspect or field. a

Whereas the participation methods do not contemplate all the possibilities of collaboration, a field box for open-end answer is intended for stating other participation paths not considered.

Question C5

This is the last question of the group and the questionnaire. The objective of this question was to verify if potential participants share the dual approach of FLasH as an incubator of LSS and closed- loop technologies not only for Space but also for Earth applications.

Appendix D. FLaSH operation

Mission requirements and drivers for future long duration human spaceflight have set technological challenges that still need to be addressed. A reference scale for measuring space technologies maturity it is provided by the Technology Readiness Level (TRL) [108]. The facility will act as a center to develop, and mature technologies as well as to conduct TRL assessments considering the steps: description, requirements, verification and viability, see Figure A 6.

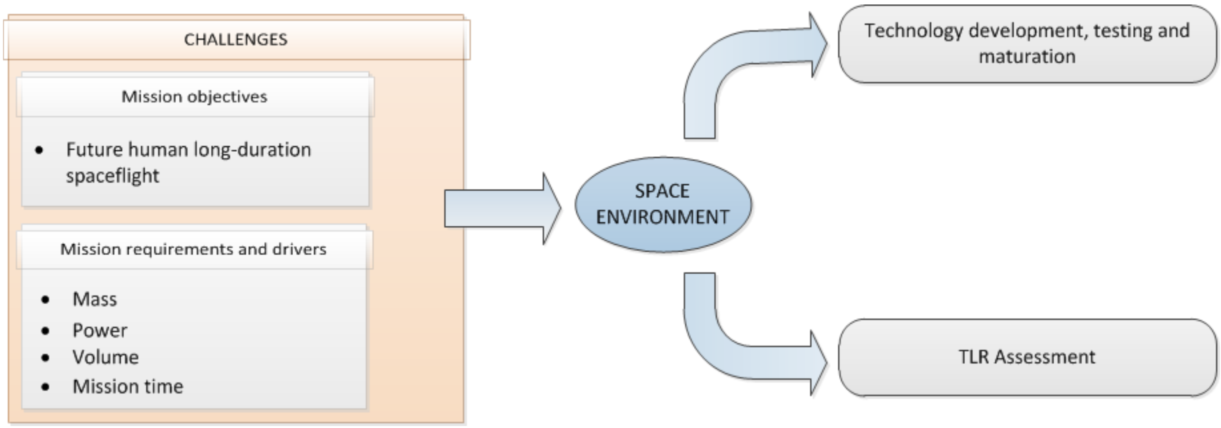


Figure A 6: Conceptual map for the Space driven technology development, testing and certification processes [72]

On the Earth challenges for environmental technology development are given by climate change, the increased necessity of efficient resource utilization and reclamation. Environmental technologies are considered to be less environmentally harmful technologies than other relevant solutions [109]. Regarding terrestrial–driven technologies validation and certification a distinction should be remarked between innovative or non-established technologies and well-established technology.

Due to their innovative content, non-established technologies hardly fit the standards or meet requirements to certify their environmental improvement. Nevertheless, their environmental improved performance can be verified with the EU Environmental Technology Verification (ETV) pilot program. In the case of innovative technologies the facility will act as a 'verification body' and should be in compliance with the requirements stated by the ISO / IEC 17020 standards [110]. The ETV will concern technologies addressing water treatment and monitoring, material wastes and resources, and energy technologies. Furthermore, additional tests could be required during the verification process for supporting tests previously done by the technology proposer. For those purposes the test facility must be in compliance with the ISO 17025 standard for the methods of testing and calibration or be certified by the EN ISO 9001.

As for the well-established technologies, the facility is intended to serve as a certification body, hence must be in compliance with the requirements of the ISO / IEC standards for certifying products, processes and services. A conceptual representation of the Earth driven technology development, verification and certification process is given in Figure A 7.

Finally, the merge of technology development for space and terrestrial applications in a single infrastructure could lead into positive impact in the technology transfer process between Space and Earth.

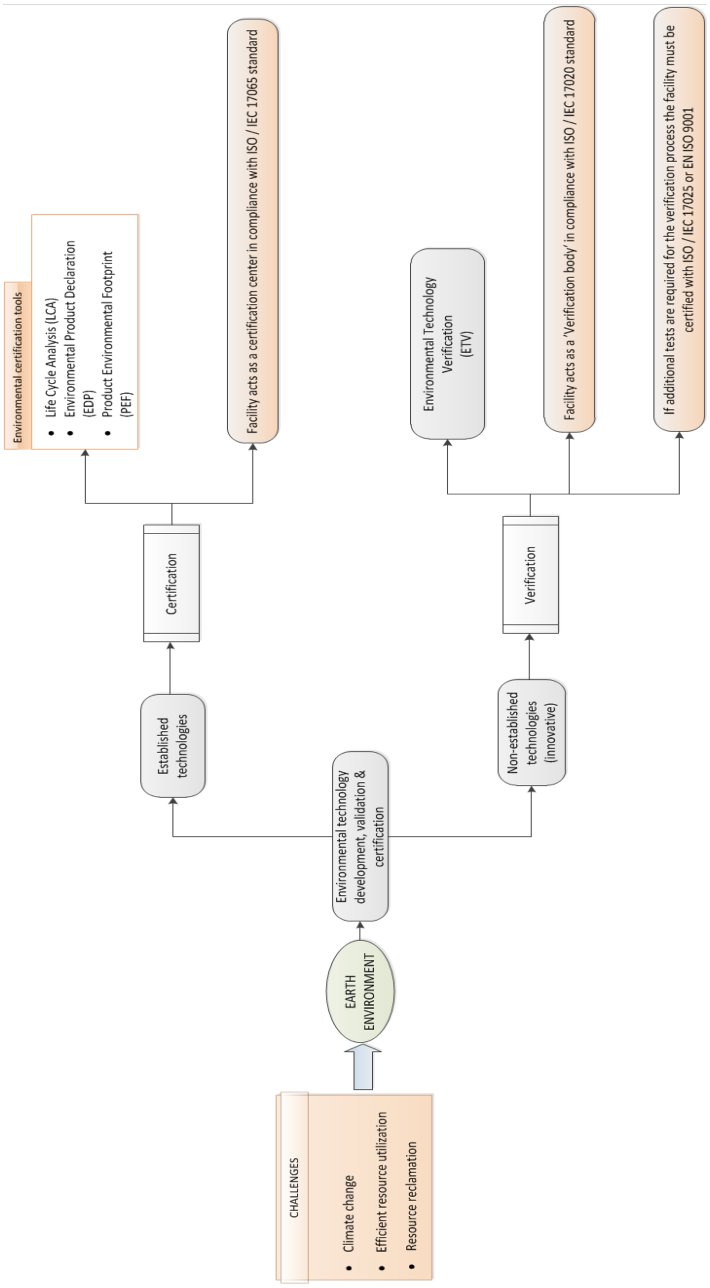


Figure A 7: Conceptual map for terrestrial technology development, testing and verification processes [72]

Finally, the merge of technology development for space and terrestrial applications in a single infrastructure could lead into positive impact in the technology transfer process between Space and Earth.

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